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Article

EVALUATION OF THE COST-EFFECTIVENESS OF GRID-CONNECTED PHOTOVOLTAIC SOLAR ENERGY IN WINERIES

AVALIAÇÃO DO CUSTO-BENEFÍCIO DA UTILIZAÇÃO DE SISTEMAS DE ENERGIA SOLAR FOTOVOLTAICA LIGADOS À REDE ELÉTRICA EM ADEGAS

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SUMMARY

The objective of this study was to analyze the cost-effectiveness of photovoltaic (PV) solar energy in wineries. The factors analysed were solar radiation, cost of PV installation, prices in the public electricity grid, size of the winery, power of installed panels, influence of the decreased consumption during weekends, and seasonality in the consumption. The study has been based on the European TESLA project, in which 39 energy audits were carried out in wineries in four European countries. A winery of 30,000 hL/year was characterized as a representative winery. The results showed that seasonality was key in the profitability of the system for self-consumption, related to the optimum power to be installed of PV. It was recommended to install, as an optimal PV power, the stable electrical power that is demanded in the daytime period. Optimizing the installed power of PV panels in the representative winery, the percentage of electrical energy consumption covered by photovoltaic energy varied between 16% and 22%. The percentage of the cost of electric energy covered varied between 18% and 24%, with payback values between 18 years (3.1 peak sun hours of solar radiation -PSH) and 10 years (5.6 peak sun hours of solar radiation - PSH). All the factors involved were analyzed.

RESUMO

O objetivo deste estudo foi analisar a relação custo-benefício da utilização da energia solar fotovoltaica (PV) em adegas. Os fatores estudados foram a radiação solar, o custo da instalação fotovoltaica, o preço da energia elétrica na rede pública, a dimensão da adega, a potência dos painéis instalados, a influência da queda no consumo no fim de semana e a sazonalidade no consumo de energia elétrica. O estudo baseou-se no projeto Europeu TESLA, no qual foram realizadas 39 auditorias energéticas em adegas de quatro países europeus. Uma adega que produz 30.000 hL / ano foi considerada como sendo representativa. Os resultados mostraram que a sazonalidade é fundamental para a rentabilidade do sistema em autoconsumo, relacionada com a potência de PV ótima a ser instalada. Foi recomendado instalar, como potência fotovoltaica ideal, a potência elétrica estável que supre as necessidades do período diurno. Otimizando a potência instalada dos painéis fotovoltaicos na adega em estudo, a percentagem do consumo de energia elétrica coberto pela energia fotovoltaica variou entre 16% e 22% e o custo da energia elétrica variou entre 18% e 24%, com valores de período de retorno entre 18 anos (3,1 PSH de radiação solar) e 10 anos (5,6 PSH de radiação solar). Todos os fatores identificados foram analisados.

Keywords: sustainability, renewable energies, net metering, self-consumption.
Palavras-chave: sustentabilidade, energias renováveis, sistema de compensação de energia elétrica, autoconsumo.

INTRODUCTION

Climate change and the reduction of greenhouse gas emissions are already a priority in many countries around the world. The increasing use of renewable energy sources is one of the specific actions aimed for this objective. In the European environment, the European Union has established several directives to promote the use of clean energy sources: three targets have been set for 2030: a 40% reduction in emissions (compared to 1990 levels); a 32% increase in the use of renewable energy sources; a 32.5% increase in energy efficiency (European Commission, 2020a). These global objectives include all sectors, including the agricultural sector, and drink industries (European Commission, 2019).

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Within the agricultural sector, wine production is a major subsector worldwide (Vela *et al.,* 2017). One aspect of interest in this subsector is that it may lead the agricultural sector's progress toward renewable energy sources (Smyth and Russell, 2009; Mekhilef *et al.,* 2013). First, wineries have a product, often with high added value, allowing them to evaluate investments that other sectors, with lower added value, cannot afford (Mazarrón *et al.,* 2012; Mazarrón *et al.,* 2013). A second aspect is that wine, as a product, depends to a certain extent on its image; investment in renewable energy sources by a winery may support the attractive image of its products. A third aspect is that the production of wine, due to its agronomic characteristics, is generally located in areas of high or medium solar radiation, which gives possibilities to solar technologies (Canas and Martin-Ocaña, 2005). Moreover, there is a fairly good seasonal match between the peak consumption in wine production and the months of highest solar radiation, since the grape harvest usually occurs in August-September in the Northern Hemisphere and in February-March in the Southern Hemisphere. The same could not be said for other agricultural subsectors such as olive oil, for instance, whose harvest is typically in November. In exchange for its advantages, a disadvantage of certain types of wineries is its seasonality. Seasonality in electricity consumption damages the profitability of photovoltaic (PV) installations (Cooperativas Agro-Alimentarias, 2016).

The European Union is the world-leading producer of wine. Between 2014 and 2018, the average annual production was 167 million hL. It accounts for 45% of world wine-growing areas, 65% of production, 60% of global consumption and 70% of exports (European Commission, 2020b). According to the European TESLA project, energy consumption in European Union wine production is around 1.750 million kWh per year, so this sector is a major energy consumer (Cooperativas Agro-Alimentarias, 2011). A winery of 30,000 hL of wine per year, selected as a representative winery in the four countries studied in the project (France, Italy, Spain and Portugal), has an average electricity consumption of about 330,000 kWh per year. In the wineries, most of the energy consumption (90%) is in the form of electricity (Fuentes-Pila and Garcia, 2014).

Within this framework of electricity consumption, PV energy has acquired a great prominence due to the reduction in the cost of the panels. The cost of the PV panel, which in 1990 was approximately $10 per Watt, is now below $1 per Watt. As a result, the overall cost of installing PV panels, including assembly and labour, is between 1 Euro and 3 € per Watt, and can be further reduced in the upcoming years (Kavlak *et al.,* 2018). This price drop has opened up a completely new scenario in the economic profitability of this solar technology.

The objective of this study was to analyze the viability and cost-effectiveness of PV solar energy in wineries. The factors studied were the following: solar radiation, cost of PV installation, prices in the public electricity grid, size of the winery, power of installed panels, influence of the decreased consumption on weekends, and seasonality in electricity consumption.

This study has been based on several previous research projects in which the authors of this work have collaborated; in particular the European TESLA project, already mentioned, in which 39 energy audits were carried out in wineries in four European countries (Fuentes-Pila and García, 2014), and the European SCOoPE project, which has deepened the characterization and evaluation of energy efficiency indexes in the agri-food industry (Services Coop de France, 2017).

MATERIALS AND METHODS

The current study has been carried out in a winery characterized in the TESLA project as a representative winery, in the European scope of four producing countries (France, Italy, Spain and Portugal). It was a winery simulated from the 39 audits carried out on the project. Its characteristics, which were as follows, constituted the base profile from which each factor influencing the process has been evaluated:

- Wine production: 30,000 hL/year.

- Main product: Red wine.

- Solar radiation on inclined surface: radiation from La Rioja, Spain (Ministerio de Industria y Energía, 1981) has been taken in the base profile: 6,171 MJ/m^2 year, equivalent to an average value of 4.69 PSH (Peak Sun Hours). Solar radiation can be measured in MJ/m^2 year or in peak sun hours (PSH), a typical value for PV that allows the energy generated to be calculated by multiplying the installed PV power by PSHs. The term PSH refers to the solar insolation which a particular location would receive if the sun were shining at 1 kW/m^2 for these number of hours. For example, a location that receives 4 kWh/m^2 per day can be said to have received 4 hours of sun per day at 1 kW/m^2, so the value of PSH would be 4. In all cases, the inclination taken for PV panels was the latitude, with panels facing south.

- Electricity consumption: 330,000 kWh / year.

Table I shows the distribution of consumption among the main processes of the winery (Vela *et al.*, 2017).

Regarding the monthly distribution, the consumptions related to the storage and aging of the wine, and offices, were distributed throughout the year, while the rest of the processes were concentrated in four months (from August to November), resulting in the distribution shown in Figure 1. Consumption related to wine storage and aging was highly variable among wineries; in some wineries the electricity consumption of this activity was relatively small, and in other wineries it was their fundamental activity. These differences were the cause of the three situations shown in Figure 1.

Regarding the daily distribution, some activities were typical of daytime (for example, reception, pressing, or offices) and others had a consumption that was distributed evenly throughout the 24 hours of the day, especially consumption in cold production (fermentation, storage and aging of the wine). This resulted in the distribution of consumption throughout the week illustrated in Figure 2.

Table I.

Power and electricity consumption of the winery processes of the base profile of the study

Process	Power (kW)	Consumption (kWh/year)
Reception	52.6	10,893
Pressing	38.4	15,986
Fermentation	165.0	91,387
Clarification	29.5	7,073
Bottling and expedition	14.8	3,112
Auxiliary activities	22.9	7,639
Storage and aging	140.3	181,821
Offices	7.3	12,089
TOTAL	470.8	330,000

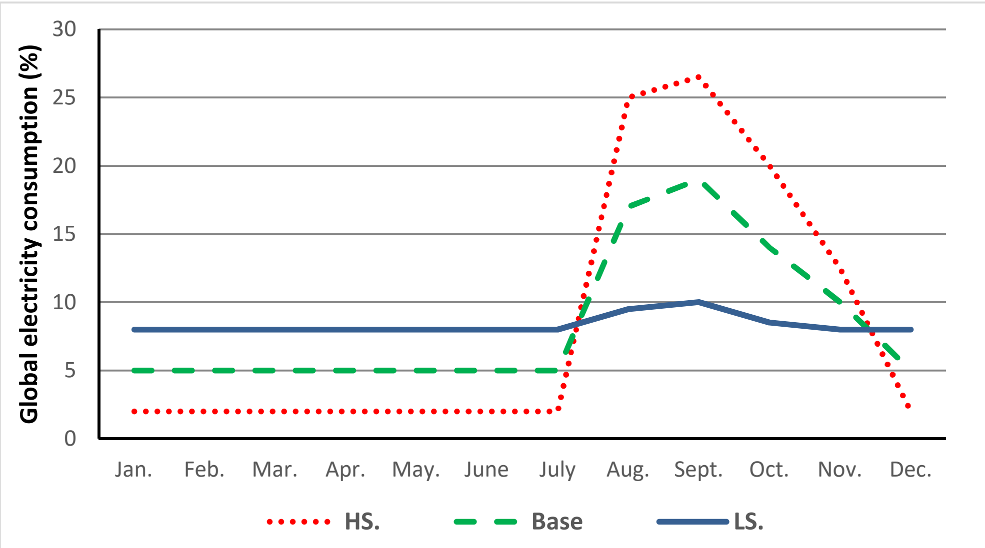

Figure 1. Seasonality scenarios evaluated: High seasonality scenario (HS), 2% electricity consumption in the eight months of lowest activity. Base profile (Base, average seasonality), consumption of 5% in the months of lowest activity. Low seasonality scenario (LS), consumption of 8% in the months of the lowest activity. These percentages have been calculated based on total annual consumption.

- Cost of purchasing electricity from the electricity grid: 0.1 €/kWh (Fuentes-Pila and Garcia, 2014). The price was different in peak, shoulder and off-peak hours (0.114 €/kWh for peak hours; 0.095 for shoulder hours; and 0.067 for off-peak - global cost, including fixed costs and taxes). Figure 3 shows the peak, shoulder and off-peak hour distribution.

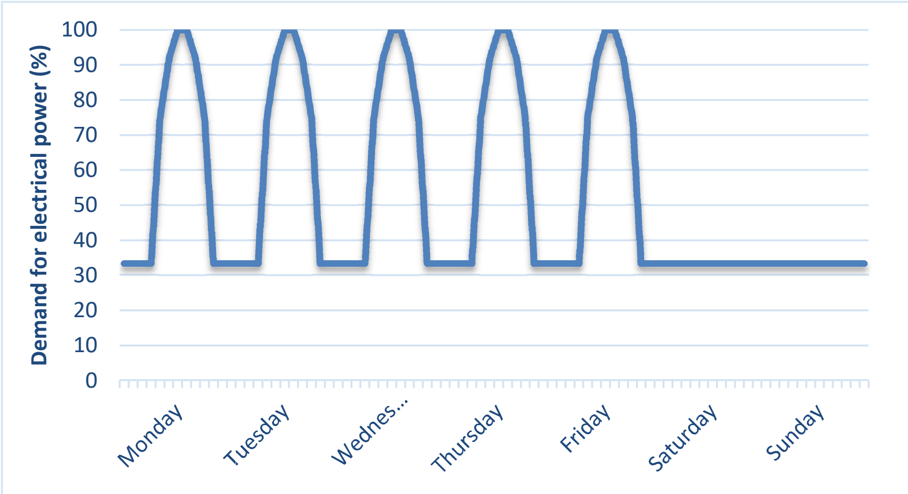

Figure 2. Typical distribution throughout the week of the demand for electrical power in wineries. Demand on weekends, in the base profile of the study, was equal to night consumption.

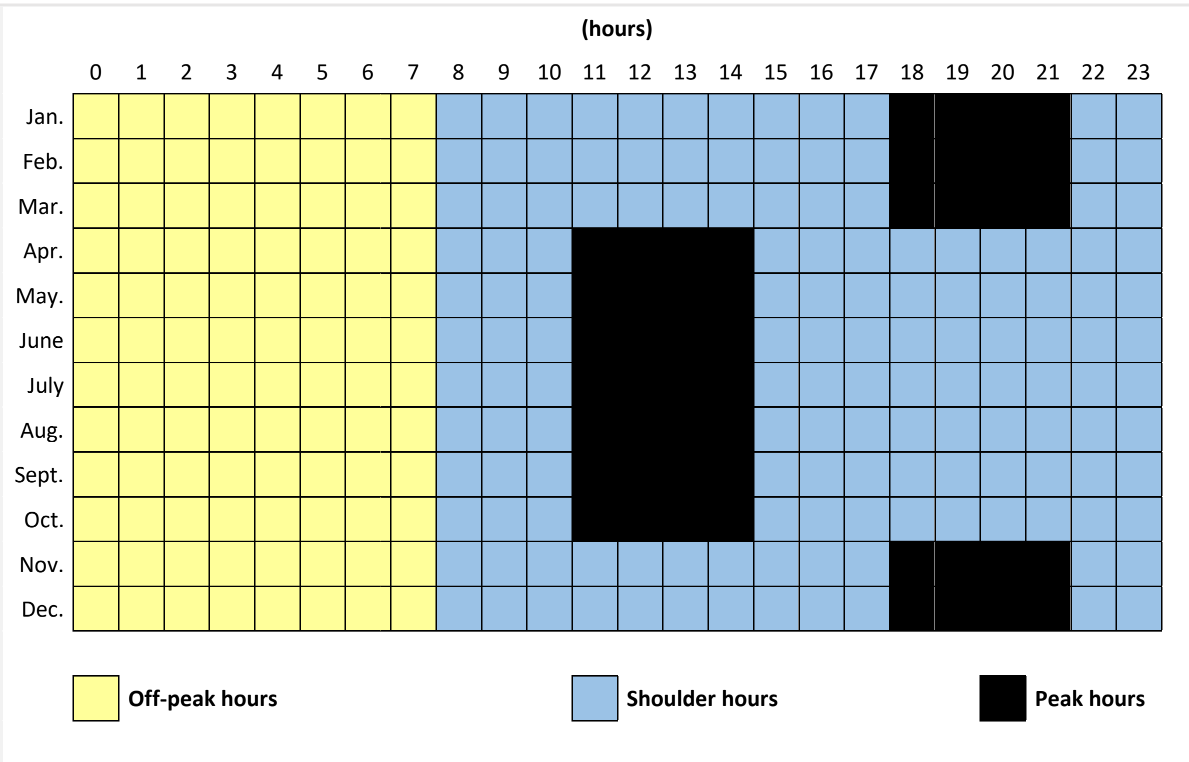

Figure 3. Monthly and hourly distribution of peak, shoulder and off-peak hours with the most common rate in wineries in Spain (rate 3.1 A).

- Seasonality: electricity consumption of 5% in the eight months of lower activity, from December to July. Consumption in the most active months: 17% in August, 19% in September, 14% in October, 10% in November. These percentages have been calculated based on total annual consumption.

- Weekly distribution of electricity consumption: The typical distribution is shown in Figure 2. Demand at the weekend, in the base profile, was equal to night consumption, as shown in Figure 2.

- In the base profile, PV solar installation was for self-consumption, without the possibility of compensating or selling surplus to the grid. Batteries were not used in this profile.

- Total cost of PV solar installation: 1.5 €/Watt-peak, including assembly and labour, without batteries (Kavlak *et al.,* 2018).

From this base profile, a number of alternatives have been evaluated, varying in each case a factor involved from the base profile, and calculating the payback for the power considered optimal. Optimal power (from an energy point of view) has been considered when 95% of the electrical energy generated by the PV panels is used in the winery. If the energy used was less than 95%, the installation was considered to be less efficient than the optimal one; if the energy used was more than 95% (if virtually all energy was used), it was considered that an additional panel surface could be installed. It should be noted that, being this study a simulation, the efficiency in the actual situation may be lower due to uncontrolled factors.

The alternatives evaluated were as follows:

- Solar radiation on inclined surface. In addition to the radiation of La Rioja (6,171 MJ/m^2 year, 4.69 PSH) the radiation of Cádiz (7,613 MJ/m^2 year, 5.59 PSH) and Orense (4,083 MJ/m^2 year, 3.11 PSH) have been evaluated. These values covered a wide range of solar radiation in the areas with wine production.

- Electricity consumption. In addition to the average winery (330,000 kWh/year), a "small" winery (158,000 kWh/year) and a "large" winery (450,000 kWh/year) have been evaluated, sizes according to the classification of Gómez-Lorente *et al.* (2017).

- Cost of purchasing electricity from the electricity grid (including taxes). Prices have been assessed from 0.06 to 0.15 €/kWh (Fuentes-Pila and García, 2014), with the corresponding proportional distribution at peak, shoulder and off-peak hours.

- Seasonality: Three scenarios have been evaluated (Figure 1). Base profile, 5% power consumption in the eight months of least activity (mentioned above). High seasonality scenario, consumption of 2% in the months of lowest activity, 25% in August, 26.5% in September, 20% in October, 12.5% in November. Low seasonality scenario, consumption of 8% in the months of lowest activity, 9.5% in August, 10% in September, 8.5% in October, 8% in November. These percentages have been calculated based on total annual consumption.

- Weekly distribution of electricity consumption. The distribution of the base profile is shown in Figure 2: weekend consumption was the minimum of the facility, typically night consumption. It has been evaluated, as alternatives, that consumption at the weekend was zero; and that it was the same as on the rest of the days of the week.

- PV installation cost values have been evaluated from 1 to 3 €/Watt-peak, including assembly and labour, without batteries.

- Installed power values of PV panels have been evaluated from 0 kW to twice the power considered optimal.

From an economic point of view, the different situations have been evaluated by calculating the payback, which could be compared with the life of the PV installation (25 years). The payback has been calculated using the following equation:

$$\text{Payback} = \text{Investment} / (\text{Savings} - \text{Maintenance}) \qquad \textbf{Eq. 1}$$

in which:

- Investment (€): calculated by multiplying the installed power of PV panels (in Watt-peak, one of the factors analyzed) by the overall cost of the PV installation per Watt-peak (€/Watt, other of the factors evaluated).

- Savings (€/year): calculated by multiplying the electricity saved by the PV installation (kWh/year), in each time period, by the cost of purchasing electricity to the grid in each time period (€/kWh).

- Maintenance (€/year): it has been calculated as the 1% annual of the investment.

RESULTS AND DISCUSSION

The concept of PV installation discussed in this study was a facility that complemented the mains power supply. The PV installation basically supplied much of the stable demand during the day, while peak demand and night consumption were supplied from the grid. For efficient installation, the design looked for almost all of the panel-generated energy to be exploited in the installation (this approach also allowed for greater cost efficiency); this criterion, at least in a first phase, limited the power of panels to the stable daytime period demand. In later phases, the installation of additional panel powers could be evaluated, whose energy will no longer be used almost entirely, but in decreasing percentages as more panels are being installed.

In this scheme, the results of the study confirmed that the optimum power to be installed from PV panels depended on the stable or minimum demand of the installation (in the daytime period), stable demand that depended on the seasonality of the winery, while the cost-effectiveness of the facility depended on the solar radiation in the area.

As shown in Figure 4, the optimal power to be installed from PV depended on the mentioned stable electrical demand, which in the standard winery defined in this study had a value of 20 kW for high seasonality, 50 kW for average seasonality, and 80 kW for low seasonality. These values in kW of stable demand were those recommended to install PV. With this design, virtually all of the energy generated by these panels will be harnessed, covering the stable demand.

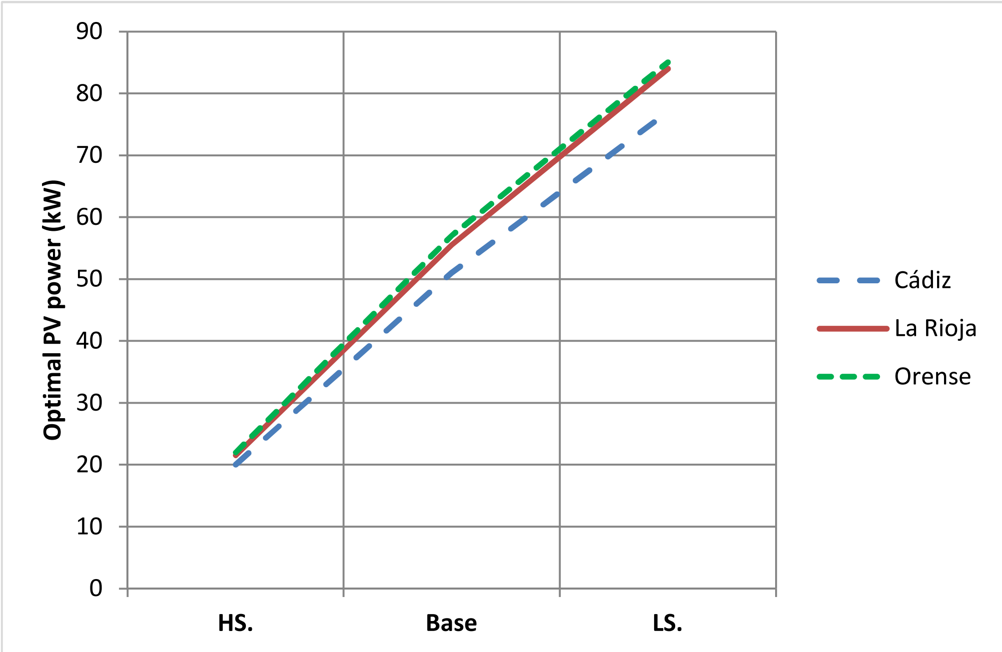

Figure 4. Optimal power to be installed from PV panels, depending on the seasonality of the winery, defined in Figure 1 (HS, high seasonality; Base, base profile; LS, low seasonality). It has been considered as an optimal power the one where 95% of the electrical energy generated by the PV panels was used in the winery (if the energy used was less than 95%, part of the generated energy is lost; if the energy used was more than 95% -virtually all energy was used-, an additional panel surface could be installed). If it was installed this power considered optimal, the payback associated with the cases of this figure did not depend on the seasonality, only on the radiation: 11.0 years, payback for Cadiz (5.59 PSH), 12.8 years for La Rioja (4.69 PSH), and 17.6 years for Orense (3.11 PSH).

Once each panel was fully utilized, the panel's profitability depended on the solar radiation of the area. The higher the solar radiation, the more energy the panel will produce and the greater savings it will produce on the electrical bill. Therefore, in this scheme, the payback did not depend on the seasonality, but on the solar radiation of the area of the winery.

The solar radiation from the three locations of this study covered approximately the entire range of Mediterranean wineries, from the maximum radiation (Cádiz) to the minimum (Orense).

The percentage of the electrical energy consumption of the winery covered by photovoltaic energy depended on the installed power, and this depended, as indicated, on the stable daytime demand. In the base profile, optimizing as indicated the installed power of photovoltaic panels, the percentage of electrical energy consumption covered by photovoltaic energy varied between 16% in Orense (the area with the lowest solar radiation) and 22% in Cádiz (the area with the highest solar radiation). The percentage of the cost of electric energy covered by photovoltaic energy varied between 18% in Orense and 24% in Cádiz, with the mentioned paybacks of 17.6 years in Orense and 11.0 years in Cádiz.

If an extreme case, is evaluated of a winery that is closed (without electricity consumption) eight months a year, the energy generated by the panels will not be harnessed during those eight months. The payback of this type of installation became more than 30 years, so the installation of PV in wineries with this type of drastic seasonality was not profitable.

Figure 5 shows the variation in profitability based on the installed power of PV, starting from the base profile, and altering the consumption pattern on weekends.

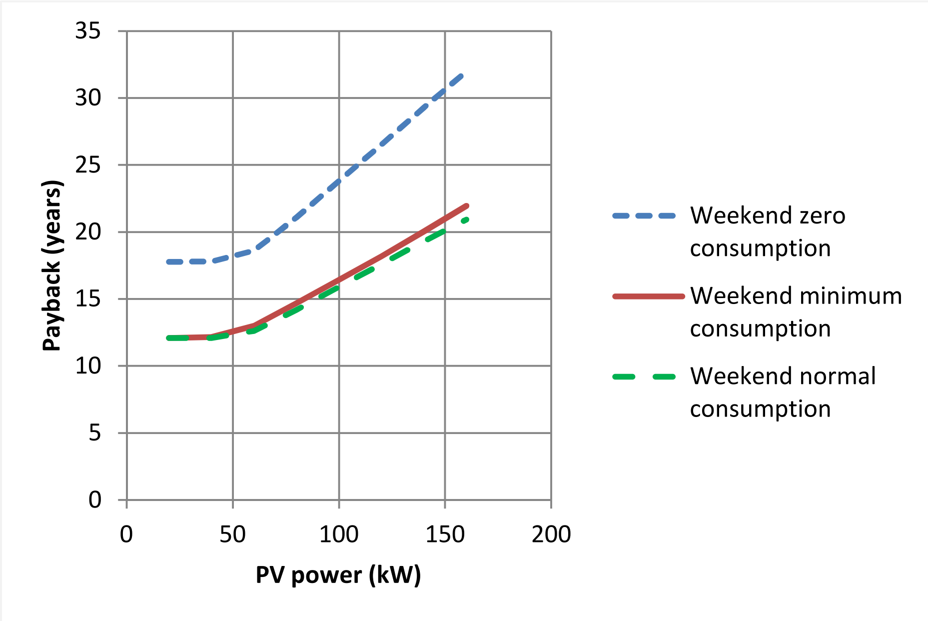

Figure 5. Variation of the payback according to the installed PV power, starting from the base profile (La Rioja), in the three situations evaluated of consumption at the weekend: zero consumption; minimum consumption (base profile, defined in Figure 2); and normal consumption as in the rest of the days of the week. Optimal base profile power: 56 kW. Base profile payback: 12.8 years.

It is noted in Figure 5 that zero consumption on weekends seriously damaged the profitability of PV energy, as it moved to a situation in which two sevenths of the generated energy were not used. The payback became much higher.

On the other hand, the situation with minimum consumption on weekends (which was equal to the night consumption in this study) was similar to the situation with normal consumption on weekends (equal to the weekday), as shown in Figure 5. For the cost-effectiveness of the PV installation, the key was the stable (daytime) presence of that minimum consumption every day of the year, without affecting much the payback the fact that the consumption on weekends presented diurnal peaks (of course, this slightly improved profitability).

Figure 5 also shows the interest of performing PV installation by phases of PV power, instead of installing the considered optimal power once. The first phase of the installation will always be more cost-effective, as shown in this Figure, as its energy will be used at 100% in most cases. The subsequent phases of expansion of PV power will be successively less profitable, since part of the energy generated no longer coincided with the one demanded by the winery, but will have the practical experience of the first phase; this will eliminate some uncertainties in the actual performance of the system. In addition, from a financial point of view, first-phase savings could help financing later phases.

If there is a practical limitation of space for the placement of panels (for example a certain space on the roof or building roof) the advantage of the situation is that those first panels are the most profitable. Situations where panels can be placed north and south, for example on a gable roof, require specific study. In the present paper, panels were considered to be facing south with an inclination equal to latitude. Other panel orientations will lead to decreases in profitability. One possible recommendation is to install the southern face of the roof in a first phase, and depending on the resulting actual situation, evaluate the installation on the north face.

Finally, Figures 6 and 7 show the influence of the purchase price of electricity on the grid, and the installation cost of the panels, on the cost-effectiveness of the PV installation.

It has not been detected in the study that the size of the winery had a direct influence on the profitability of PV energy. However, size can have an indirect influence, due to two factors. According to Gómez-Lorente *et al.* (2017), large wineries get (on average) a better price in buying electricity in the grid. For this reason, by getting the most expensive electricity, the cost-effectiveness of PV panels would be higher in small wineries (Figure 6). On the other hand, large wineries, if they have a larger PV installation, by economy of scale, could have a lower cost of PV installation (per unit of Watt-peak; Figure 7). However, it should be taken into account that the power of PV panels to be installed depends on stable daytime consumption, so there will not always be a direct correspondence between the size of a winery and the optimum size of its PV installation.

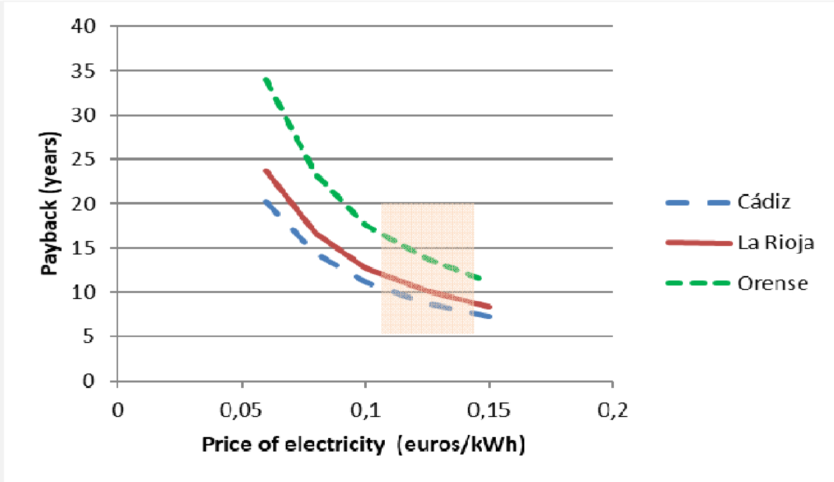

Figure 6. Variation of the payback based on the purchase price of electricity in the grid, for three locations. According to Gómez-Lorente *et al.* (2017), this price is 0.115 €/kWh for large wineries, 0.125 for medium wineries, and 0.142 for small wineries. This price range is marked in pink on the graph.

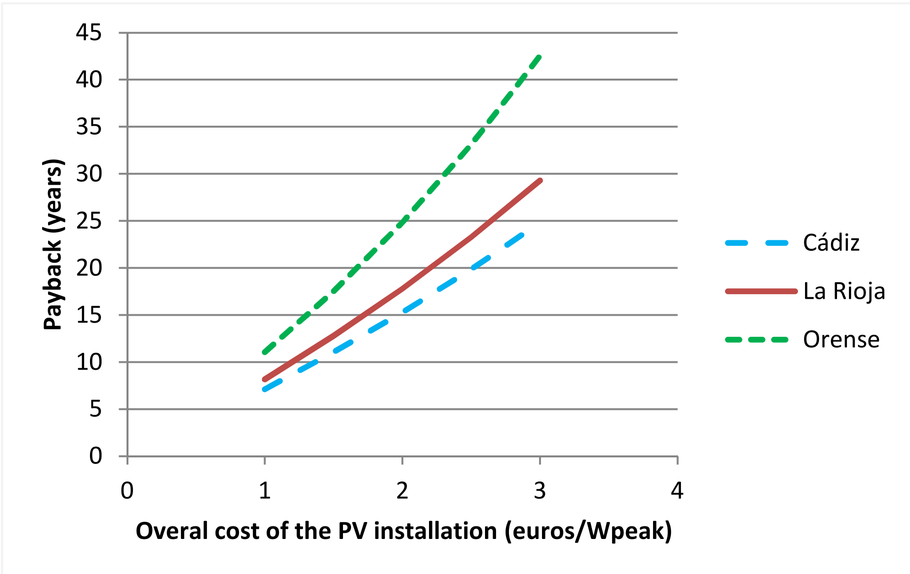

Figure 7. Variation of the payback based on the overall cost of the PV installation (including assembly and labour), for three locations with different solar radiation.

In summary, the size of the winery did not have a direct influence on the profitability of PV energy; there might be an indirect influence through the price of electricity, or the cost of PV installation. The influence (on profitability) of the cost of PV installation could be somewhat greater than the influence of the purchase price of electricity, as shown in Figures 6 and 7.

Finally, Figure 8 presents the comparison between the situation without selling energy to the grid, and with the sale of energy to the grid. The difference was minimal with PV powers lower than the one considered optimal in the base profile (since virtually all the energy generated was consumed in the installation itself). If higher PV power is installed, profitability begins to be different between sales and non-sales situations.

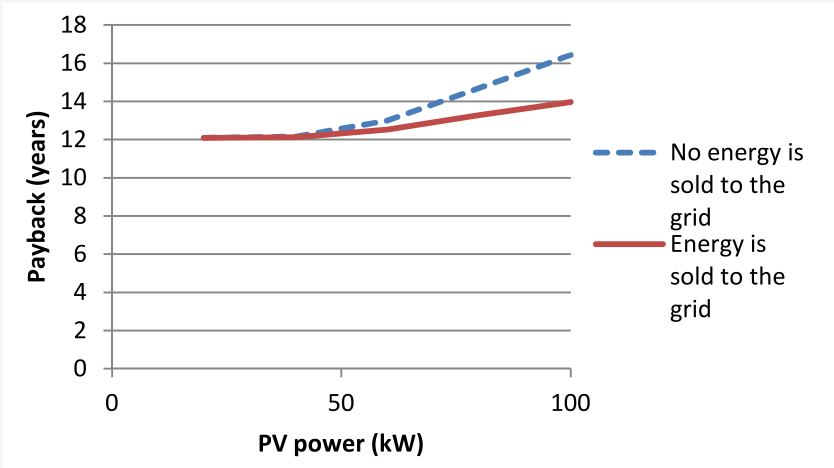

Figure 8. Variation of the payback according to the installed PV power, comparing two alternatives: the alternative in which no energy was sold to the grid (base profile), in relation to the situation in which energy was sold to the grid, at a fixed price of 0.05 €/kWh (Gómez-Lorente *et al.,* 2017). Optimal base profile power (without sale to the grid): 56 kW. Base profile payback: 12.8 years.

In wineries, PV solar energy seemed a good technology to integrate into the constructive designs, rather than an alternative to construction designs of almost zero energy consumption, since it seems inevitable that a winery has a certain electrical consumption, and this could be supplied in a large part with PV energy. If the regulation allows selling or compensating surpluses, globally the PV installation of the winery can generate the same amount of electrical energy that the entire winery consumes, although in certain periods the energy is taken from the grid.

The limited time span (4 to 5 months) of annual consumption of wine manufacturing clearly calls for additional synergies that must be explored in the agricultural implementation of PV, aimed at solar-powered agriculture. From the results of the study, it seems clear that additional electric consumption in the rest of the months (in wine storage or aging) can flatten the total annual consumption curve and render profitable the larger-kW installations. Other uses of the electricity are possible: for example, in water pumping or irrigation. Currently, there are also solar-fuel solutions underway to allow a cost-effective storage of solar electricity in synthesized fuels, which can be a great solution to circumvent the PV intermittency problem (Vieira *et al.*, 2019; Lourenço *et al.*, 2020). Moreover, neighboring agro-industries can share their electrical PV production in order to increase their energy efficiency and their environmental compliance (Latini *et al.*, 2018). A key outcome is that PV installation should be synergetic, and possibly not just focused in one particular manufacturing or consumption process in agriculture, in order to take most annual profit.

It is important to point out that the current values taken for the costs of the PV corresponded to current data that is always in permanent evolution, and is likely to suffer considerable variations in the coming years. Regarding solar electricity, its cost-per-Watt is expected to keep falling with the development of PV technologies based in higher-efficient solar cells and/or more affordable thin-film PV materials (Enrichi and Righini, 2019; Centeno *et al.*, 2020).

CONCLUSIONS

There are three factors which can initially influence the profitability of a grid-connected PV installation for self-consumption in wineries: the solar radiation ; of the area; the cost of the PV installation; the purchase price of the electricity. In a winery with these three factors at the usual levels in the Mediterranean area (base profile of the study), the PV installation evaluated was profitable, with values of payback between 10 years (5.6 PSH of solar radiation) and 18 years (3.1 PSH of solar radiation).

Seasonality was the key in the profitability of the system for self-consumption, related to the optimum PV power to be installed. It is recommended to install, as an optimal PV power, the stable electrical power that is demanded in daytime along the year. If consumption is very low or zero in certain day periods, the profitability of PV is low: for example, if consumption is zero for eight months, PV energy is not profitable.

The percentage of the electrical energy consumption of the winery covered by photovoltaic energy depended on the installed power, and this depended, as indicated, on the stable daytime demand. Optimizing the installed power of photovoltaic panels in the average winery, the percentage of electrical energy consumption covered by photovoltaic energy varied between 16% (in the areas with the lowest solar radiation) and 22% (in the areas with the highest solar radiation). The percentage of the cost of electric energy covered by photovoltaic energy varied between 18% and 24%.

It is recommended to carry out the installation of PV in phases. The first phases are the most cost-effective, as if there is stable day demand, virtually all electricity generated by the panels is utilized. The following phases are less cost-effective, because some of the electricity is no longer used. More PV power can be installed, with good profitability, if electricity can be sold to the grid, or surplus compensation can be obtained.

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