

Article

Economic Evaluation of PV Installations for Self-Consumption in Industrial Parks

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Abstract: This paper presents an analysis of the economic performance of photovoltaic (PV) self-consumption systems at an industrial park in the Basque Country (north of Spain). The economic feasibility of the installations is largely dependent on self-consumption and compensation due to electricity injected into the grid, as well as the assumed evolution of the electricity prices. A sensitivity analysis is carried out for different installation sizes and different evolution scenarios concerning electricity prices. The potential for installations for shared self-consumption with dynamic and static distribution coefficients is also analyzed. The results show that medium sized installations are generally a cost effective way to reduce energy bills, while the economic performance of larger installations is more uncertain, and is largely dependent on the selling price for electricity injected into the grid. This case study found that the economic benefits of shared self-consumption between different companies are substantial, and are slightly more favorable when applying dynamic distribution factors.

Keywords: photovoltaics; legislation; renewable energy; industrial parks; sustainability; self-consumption; LCC



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1. Introduction

The industrial sector, which depends heavily on energy prices to maintain competitiveness, is facing a paradigm shift in which economic sustainability in itself is insufficient to allow it to prosper. Instead, it must be accompanied by environmental sustainability, which entails moving towards a low-carbon and environmentally friendly economy. In fact, the industrial sector plays a fundamental role in national strategies of decarbonization, as reflected in the new European industrial strategy [1] launched in the framework of the new European green deal. Furthermore, at the national level, the National Energy and Climate Plans [2] are also working on this same line of action, highlighting the need to maintain a sustainable yet competitive industry.

Considering the reduced costs of solar energy in recent decades [3] and its the reduced environmental impact [4], solar PV is regarded as a very good alternative to traditional energy sources. In countries with high solar irradiance, very high profitability can be achieved for large PVPP plants. This is shown in the calculations by Alshare et al. [5], who predicted an internal rate of return (IRR) over 30% for a photovoltaic power plant (PVPP) of 5 MW in Jordan. In Spain, which also has high levels of irradiation [6], Menendez and Loredó [7] showed that although highly dependent on electricity prices, an IRR of nearly 10% could also be achieved for a large 400 MW PVPP. Installations of a smaller scale integrated into buildings are not very profitable at the moment due to the economy of scale required to operate in the electricity market, but there is an opportunity to improve the economic performance of PVPP when used for self-consumption.

A new regulation for self-consumption was put into place in Spain in 2019 (RD 244/2019) [8]. The introduction of this new legal framework has meant the repealing of one of the

most restrictive regulations in the world [9,10]. It has introduced a favorable context for renewable energies of distributed generation and self-consumption, allowing business models and generation schemes to emerge that enable their economic feasibility [11]. Consequently, self-consumption has become an increasingly attractive alternative that goes along with the growing evolution of PV technology [12]. The aforementioned legislation is expected to provide strong support for the development of self-consumption systems [13]. The most important modifications introduced by this new legislation include the revocation of the “sun tax”, the elimination of installed power limits, and the consideration of shared self-consumption.

Moreover, it defines several modalities for self-consumption:

1. No surpluses: This refers to installations where all the energy produced is employed to meet electricity demands. It requires an antidumping system in case surpluses occur.
2. With surpluses: Surplus energy will be fed into the grid. This mode is further divided into two subcategories:
 - WITH compensation: When surplus energy from the PV system is available, it can be injected into the grid to be valued at the average price of the hourly electricity market and subtracted from the cost of the energy purchased from the grid during the same invoicing period (1 month). In no case can the result be negative. The installed PV power capacity cannot be greater than 100 kW.
 - NO compensation: In this case, the surplus will be sold on the electricity market. Additionally, the owner of the installation must register as an energy producer and will be subject to the corresponding taxes. All self-consumption with surpluses that do not comply with the requirements of the previous modality, or that voluntarily choose not to take advantage of it, will belong to this modality.

In addition to the self-consumption modalities mentioned above, RD 244/2019 also introduces a new “fixed distribution coefficient” in the case of shared self-consumption with surpluses. This ratio pre-establishes the property of the energy produced by the solar panels by assigning to each consumer a fixed percentage of the production, instead of using dynamic distribution coefficients, considering the instantaneous consumption of each building to ensure the highest self-consumption rate at any moment.

In the industrial sector, which generally includes large roof areas in industrial buildings, the potential for self-consumption of electricity generated from PVPP is very high, and generally can bring considerable economic benefits compared to PVPP built for exporting electricity to the grid. How this new legal framework will affect the deployment of new PV systems for distributed generation, and to what extent industrial actors will benefit from this measure to improve their competitiveness are questions yet to be answered. While the new regulation offers new opportunities for improving the profitability of PVPP for self-consumption and shared self-consumption between different companies, the introduction of the fixed distribution coefficient limits possible synergies among consumers and the maximum profitability that can be obtained from a PV plant.

This study will focus on analyzing the influence of the distribution coefficient for shared self-consumption of electricity generated by PVPP in the industrial sector. The economic analysis differs from that of conventional PVPP [14–17], as a good dimensioning of the system relating to the hourly energy use of the different industrial consumers is key to obtaining the maximum performance of the power plant, both economically and environmentally. A sensitivity analysis will also be presented to evaluate the results, taking into account the fact that uncertainty surrounding future electricity prices has a major influence on the profitability of PV plants.

2. Materials & Methods

The purpose of the study is to evaluate the impact of current legislation on the economic and environmental performance of a Photovoltaic Power Plant (PVPP) in an industrial facility for self-consumption with surpluses. The influence of certain variables

over the final profitability of a range of possible scenarios will be presented, along with a recommendation for legal frameworks which are more favorable for the deployment of distributed energy systems. A wide range of possible installations will be calculated for each scenario in order to identify the best possible solution.

The industrial complex studied was the Okamika Industrial Park. It is located in the Basque Country (north of Spain, radiation in the horizontal plan of 1235 kWh/m²·year) and is comprised of about 30 companies distributed in six pavilions [18]. The economic activities in the industrial park are predominantly associated with the cardboard packaging and rubber manufacturing sectors. For the purpose of the study, the electricity consumption values for companies in three pavilions of the park have been accessed. These companies are distributed in three halls: P1B, P2 and P3 (see Figure 1).



Figure 1. Geographical location of industrial halls under study and denomination correspondence.

2.1. Energy Performance Characterization

For this study, hourly PV production calculations were made in compliance with the norm for energy performance of the buildings. The method used for the calculation of system requirements and system efficiencies is located in Parts 4–3: heat generation systems, thermal solar, and photovoltaic systems. Module M3-8-3, M8-8-8-3, M11-8-3'' [19]. Irradiance data was accessed from the *PVGis* database [20]; considering the inclination and orientation of the industrial premises, with a slope of 15° and an azimuth of −40°, it corresponds to installations directly mounted on the roofs of the pavilions.

$$E_{PV} = \sum_{h=1}^{8760} \frac{P}{k} \cdot I_{plane} h \eta_G$$

E = energy produced by the PV panels [kWh]

P = installed power [kW]

k = power density factor [kW/m²]

I = hourly solar irradiance on the plane (slope = 15°; azimuth = −40°) [kW/m²]

η_G = global efficiency of the system (this includes: miscellaneous losses (13%), mean annual temperature losses (8%), and inverter efficiency (95%), and results in 76% efficiency, which equals [19] reference value). Real electricity consumption data were extracted from smart meters and energy bills on an hourly basis for the year 2019. The consumption patterns of the industrial park reached their maximum between 10 h and 12 h (see Figure 2a), showing a second relative maximum at around 17 h. There is a clear decrease in electricity consumption in the summer months (July–August); see Figure 2b.

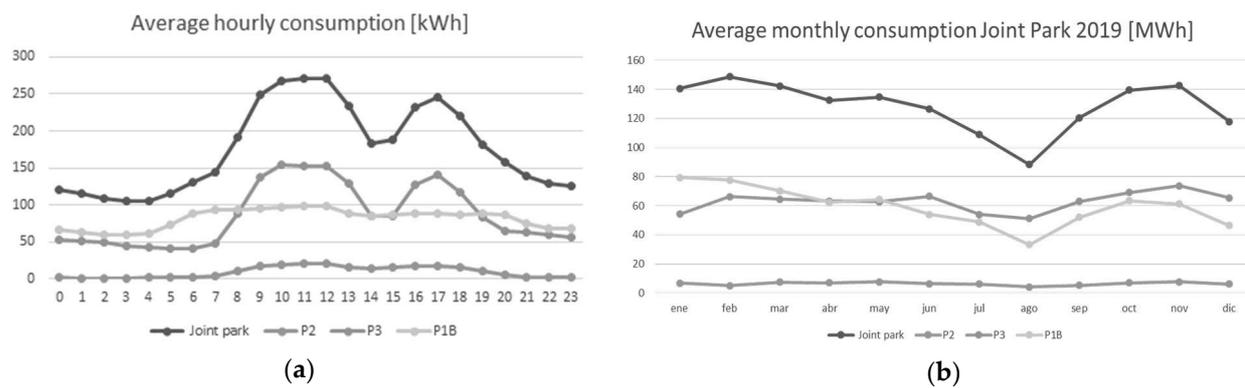


Figure 2. Energy characterization of industrial halls under study. (a) Hourly average energy. (b) Monthly average energy consumption.

The electricity consumption curve shows valleys in the periods with the highest potential for PV production, as the central hours of the day and the summer months show periods of lower industrial productivity. This pattern in the consumption curves will have a great influence on the optimal dimensioning of the PV installation. For example, if the objective is to optimize the installation to avoid the injection of energy into the network, the resulting installation would be enormously limited in terms of installed power capacity, as the days of greatest production are coupled with those of least consumption.

For the study of the installation, a commercial monocrystalline panel [21] was taken as a reference and its catalogue data was extracted. The same procedure was then followed for the inverter. Table 1 shows, in detail, the efficiency parameters used for the energy performance of the PV installations.

Table 1. PV system technical parameters used for calculations.

Parameter	Value
PV module efficiency	19.4 (%) [21]
Miscellaneous losses	13(%) [22]
Inverter efficiency	95(%) [23]
Power density factor-k	0.165 [kW/m ²] [19,21]

2.2. Energy Balance Characterization

Once energy production and consumption data were available, the relevant parameters for the energy balances were calculated for every hour of the year.

For $h = 1$ to 8760:

$$\begin{aligned} \text{if } E_{PV} \geq E_c &\rightarrow E_{SC} = E_c; E_{surplus} = E_{PV} - E_c; E_{grid} = 0 \\ \text{if } E_{PV} < E_c &\rightarrow E_{SC} = E_{PV}; E_{surplus} = 0; E_{grid} = E_c - E_{PV} \end{aligned}$$

where:

- E_c = electricity consumption [kWh]
- E_{PV} = electricity produced by the PV system [kWh]
- E_{SC} = electricity self-consumed in the corresponding time period [kWh]
- $E_{surplus}$ = electricity surplus injected into the grid [kWh]
- E_{grid} = electricity consumed from the grid [kWh]

2.3. Economic Performance Characterization

The economic performance was calculated according to EN 15459-1 Energy Efficiency in Buildings: Procedures for the Economic Evaluation of the Energy Systems of Buildings [24], resulting in the following equation. The evolution of the operational and maintenance cost is reflected in the discount rate. The pricing of the inverter that will be

renewed in year 15 is assumed to be constant, given its relatively flat behavior in the recent years [25], low contribution to the total cost of the system [26], and uncertainty regarding its future evolution: on the one hand, technological development and economy of scale might cause the price to drop; on the other, more demanding grid protection mechanisms may result in an increase in inverter hardware prices [27].

$$NPV = -C_0 + \sum_{i=1}^I \frac{\sum_{t=1}^T [(E_{SC\ t} * C_{EP\ t}(1 + EPVR)^i)] + (E_{Surp} * C_{MP}(1 + EPVR)^i) - C_{O\&M} - C_{R\ i}}{(1 + discount\ rate)^i}$$

where:

C_0 = initial investment costs

$E_{SC\ t}$ = electricity self-consumed in the corresponding time period (T) [kWh]

$C_{EP\ t}$ = electricity price for industrial customers in the corresponding period (T) [€/kWh]

EPVR = Energy Price Variation Rate [%]

E_{surp} = energy surpluses [kWh]

C_{MP} = electricity market price [€/kWh]

$C_{O\&M}$ = operation and maintenance costs [€]

C_{RI} = equipment renewal costs [€]

T = time period of the electricity tariff (see Figure 3)

4 “peak” hours (orange): 0.147€/kWh

12 “flat” hours (light green): 0.124 €/kWh

8 “valley” hours (dark green): 0.090 €/kWh

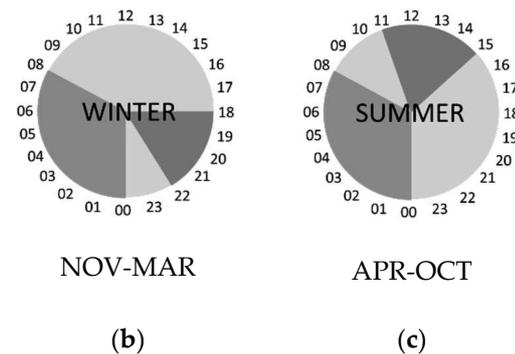


Figure 3. Hourly electricity rates for industrial customers. Tariff 3.0A Iberdrola. (a) electricity prices according to consuming periods (b) winter time periods definition (c) Summer time periods definition. [28,29].

The prices associated with the consumption of electricity, which will define the savings obtained by the PV installation, correspond to the current tariff. Prices were extracted from the most recent energy bills and divided into three time periods (T1, T2, or T3) and summer and winter seasons (Iberdrola 3.0A tariff) [28,29].

The retail price for the electricity injected into the grid was set at 4.7 €/kWh, based on calculations of the average price on the Spanish daily market for the year 2019 [30].

The temporal scope of the study was set at 25 years, which corresponds to the estimated lifetime of a PVPP, considering the renewal of the inverter in year 15. Furthermore, an annual electricity price variation rate (0.75%) was considered based on the slope of the linear regression, calculated using the electricity prices for nonresidential consumers in Spain, which included taxes and was collected by Eurostat between 2007 and 2019 [31]. As shown in the following sections, it is a determinant parameter for the profitability of the PVPP. As an alternative solution to other energy price projection methods, a sensitivity analysis is proposed that includes all possible scenarios. Moreover, in the sensitivity analysis and discussion sections, the influence of this parameter on the results will be further analyzed due to the uncertainties surrounding its future evolution, especially in scenarios with deep PV penetration, which could result in a drop in electricity prices in the central hours of the day.

An estimation of the installation costs was obtained from EVE (Energy Agency of the Basque Government) [32], which establishes three power ranges and their associated costs, reflecting the benefits of economies of scale (see Table 2). Maintenance and inverter costs were obtained using estimates provided by UNEF [33], and are presented in Table 3.

Table 2. PV installations reference costs [32].

Rated Power	Reference Cost [€/Wp]
<10 kW	1.5
10 kW–100 kW	0.9
100 kW–1 MW	0.75

Table 3. Economic parameters used for economic performance calculation.

Parameter	Value
Mean annual electricity price variation rate	0.75(%) [31]
Interest rate	7.1(%) [34]
PV modules service life	25 (years) [4]
Inverter service life	15 (years)
Maintenance cost	0.02 €/Wp·year [33]
Inverter cost	0.2 €/Wp [33]

In addition to the installation and operational costs, other aspects were also considered, including the annual variation in the price of electricity and interest rates. To evaluate the economic performance, the Internal Rate of Return (IRR) was chosen as the main indicator, considering 7.1% of the reasonable rate of return for renewable installations [34]. As can be seen throughout the article, variations in the price of electricity take on a special meaning when considering the final profitability of the installation, as they directly influence the savings generated. Given the uncertainty surrounding the evolution of that value, a sensitivity analysis was applied to evaluate the performance of the facility in multiple scenarios.

3. Results

According to the methodology explained above, five possible cases for the PV installations in Okamika Industrial Park are presented. Three installations (in Halls P1B, P2, and P3) correspond to individual installations in each one of the buildings. The fourth installation corresponds to a joint installation for shared self-consumption with static factors, which is compliant with the current legislation that pre-establishes the property of the electricity to be produced, and as such, does not allow for an optimum distribution of self-produced electricity. Finally, the fifth case represents a joint installation for shared self-consumption with dynamic factors. These dynamic factors or dynamic distribution coefficients consider the instantaneous consumption of each building, and ensure that the energy produced is distributed among consumers, maximizing self-consumption and minimizing energy injection into the grid.

The results of the study allow us to determine the optimal dimensioning of a PV power plant in every case. When considering the economic profitability of the installations, there are three main factors that will determine the optimal size:

- First, the economy of scale will greatly affect the price of the installed kW by favoring larger installations.
- Second, larger installations will inevitably cause a greater surplus, which means substantially less income generated than that saved by self-consumption, therefore reducing the profitability per installed kW.
- Lastly, legislation limits the possibility of self-consuming the produced energy among the consumers connected to the same PV plant. This will affect profitability, as larger injections into the grid will reduce the income generated.

The combination of these factors favor bigger installations, as long as it is possible to self-consume the produced energy. Once the installation begins to feed energy into the network, the profitability decreases progressively due to the lower value of the kWh sold in the network compared to the value of the energy saved. Figure 4 shows the results of the analysis of the five cases considered.

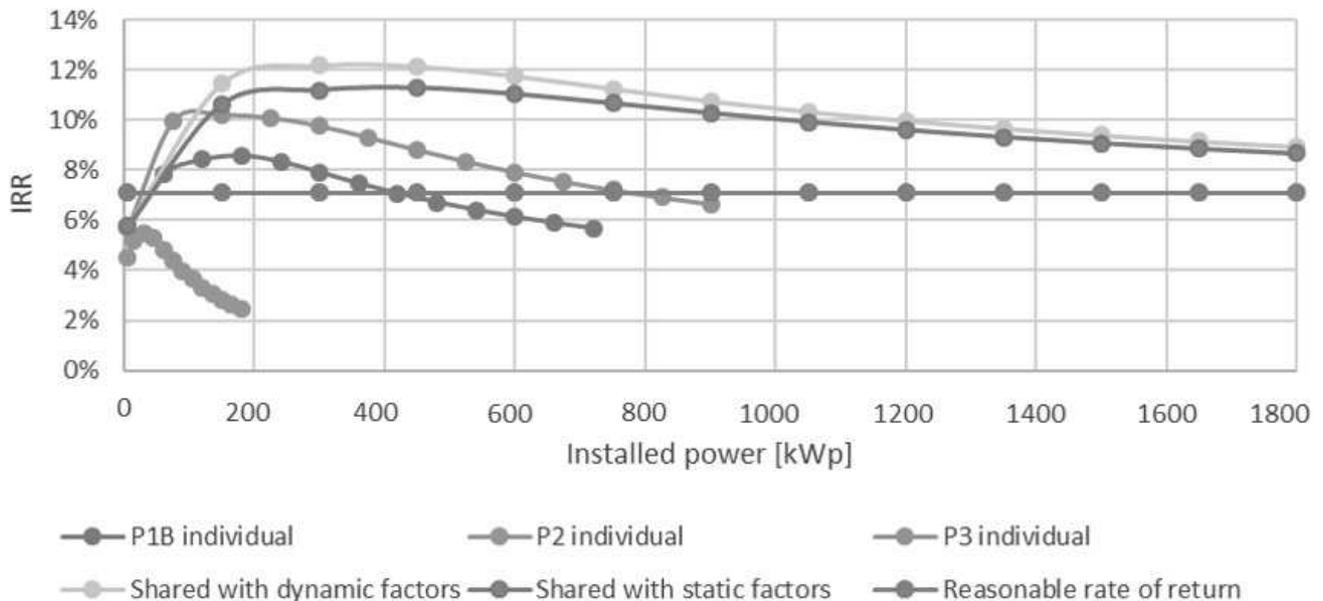


Figure 4. IRR of the PV production plant for each one of the five scenarios, according to the installed power [kW].

As shown in Figure 4 for the installation in Hall P1B, the profitability curve reaches its maximum between 100 kW and 200 kW. For those installed capacities, the costs of the installation per kW is lower than for smaller installations, and a high percentage of the produced kWh is still dedicated to self-consumption. For larger installed capacities, the profitability decreases progressively due to a greater amount of energy injected into the network that is rewarded at a lower price.

It can also be seen that Hall P3 shows a higher IRR (around 2 percentage points) than Hall P1B, despite having annual consumption values of the same order. This variation in profitability is directly related to the coupling of the production and consumption curve. As shown in Figure 2b, Hall 1B shows greater seasonal variability in its consumption, with a greater reduction in the summer period, thus not allowing a high rate of self-consumption when PV production is at maximum levels. This does not occur in Hall P3, which has similar electricity consumption for every month of the year. Another positive factor for the rising profitability of Hall P3 is that maximum consumption occurs around 12:00 p.m., facilitating the coupling of production and consumption, despite the fact that a relative minimum is reflected at 3:00 p.m.

The calculations made for Hall P2 show that the profitability of the installation does not reach the reasonable profitability threshold of 7.1% at any time. This is due to the low annual consumption values shown by the company for this installation, in which only small installations (<25 kW) with relatively high cost per kW installed ensure a percentage of self-consumption above 50%. In this case, larger installations would mainly be used for exporting electricity to the grid, which decreases the IRR.

In the case of shared self-consumption installations of the whole industrial complex, there are substantial economic benefits resulting from the economy of scale that can be observed.

In the case of a joint installation, applying static coefficients, the range of installation with a good profitability margin (IRR > 10%) extends above 1 MW installed capacity. If dynamic factors are applied, allowing for a distribution of the produced energy as

needed by the different companies, the overall IRR of the installation would improve in approximately 1% of medium sized installations; this is the result of a greater percentage of energy being self-consumed, rather than injected into the grid. For larger installations, where more electricity is injected into the grid, either with static or dynamic factors, the profitability in both cases progressively diminishes and converges.

In Figure 5, an example of the energy balance between energy production and consumption is depicted in the case of a joint installation with static coefficients. Here, it can be seen that for a 200-kW installation, a large share of the electricity is self-consumed, and the IRR rate in this case is considered attractive at 10.9%. Larger installations have the benefit of economy of scale, but the share of self-consumption is reduced, and more energy is injected into the grid at a lower price. In this case, 450 kW corresponds to the highest IRR rate, as it adapts best to the energy consumption patterns of the industrial complex, while benefiting from some economy of scale.

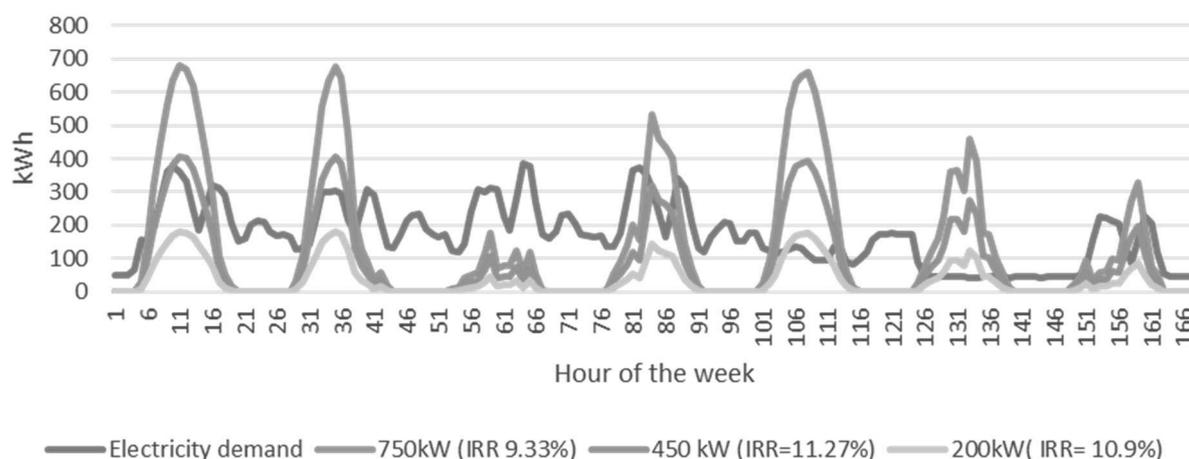


Figure 5. An example of energy balance over a week for different possible PV installed power, and the respective IRR in the case of static coefficients.

4. Sensitivity Analysis

When performing the calculations, it was observed that the results were highly dependent on the variation rate of the electricity price. In fact, electricity prices in the future are highly uncertain and the introduction of renewable energy, demand variability, carbon pricing, and new technological developments could re-shape the electricity market [35]. These changes could mean, for example, the inversion of the energy production curve, and a consequent drop in the price of electricity on sunny days, which has already been observed in California [36]. The uncertainty surrounding this parameter could cause investors to lose trust in this type of installation, and demobilize their investments in distributed renewable energies that have very high decarbonization potential. Consequently, a sensitivity analysis that would include all probable scenarios in the future is proposed. This would make it possible to evaluate, under multiple scenarios, the economic performance of the facility. After this analysis is performed, it will be clear that even in the most pessimistic scenarios for self-consumption (lower price of grid electricity), if the installation is sized correctly, the profit margins would justify these investments.

In order to foster a better understanding of the results, only the figures for the two most profitable installations are shown.

Figure 6 shows the strong influence of electricity prices on profitability in the five case studies, with differences of up to 5 points in the calculated IRRs for specific PV installations. However, it is remarkable how shared self-consumption makes them more resilient to these changes, and it is possible to ensure an acceptable rate of return in even the most pessimistic scenarios (those in which the price of grid electricity decreases). Furthermore, it is also noteworthy that shared installations favor greater installed power, favoring the integration

of distributed renewable energy. Similar to Figure 4, Figure 6b shows how the solar installation in pavilion B has an IRR below 7.1% that is considered to be a reasonable return of investment. The sensitivity analysis result highlights the importance of performing a detailed analysis before investing in a self-consumption plant.

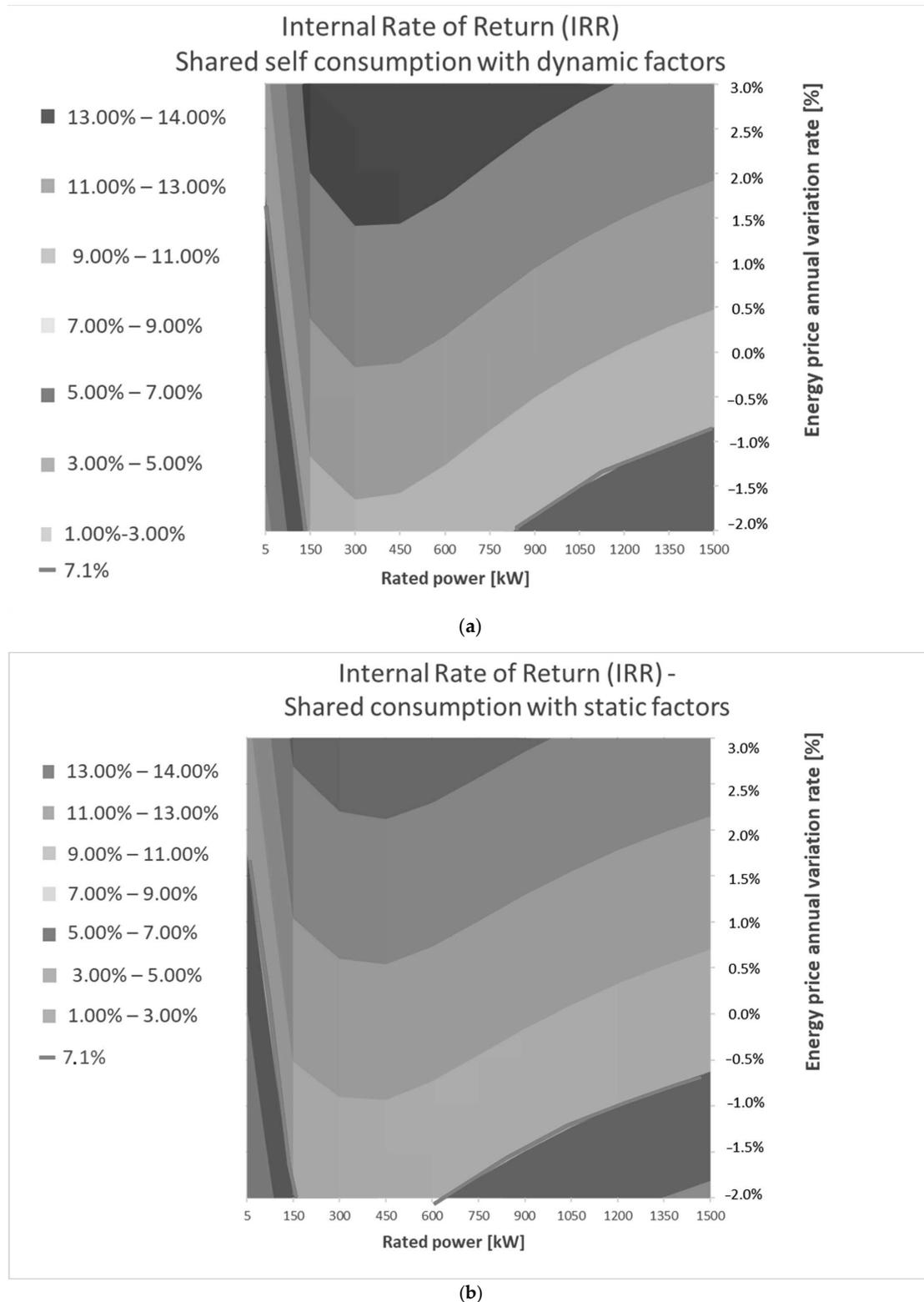


Figure 6. IRR as a function of energy price variation rate and installed power for a shared installation with dynamic (a) and static (b) coefficients. The yellow and green depict all the possible scenarios where the IRR is above the Reasonable Rate of Return for PV installations, marked by a red line. The situations where this minimum profitability threshold would not be achieved are shown in grey.

5. Discussion and Conclusions

This study presented an economic evaluation of PV installations for self-consumption in industrial facilities. In all cases analyzed, with the exception of the individual installation in P2, the IRRs were above what may be considered a reasonable rate of return for the investment. Installations were shown to reduce electricity bills, a key factor in ensuring their competitiveness. It has also been shown how a good sized installation, taking into account a correct coupling between production and consumption, and economy of scale, are determining aspects of the return on this type of investment, even in scenarios where the evolution of the price of electricity involves great uncertainty.

This study highlights the potential benefits of different companies in industrial parks sharing renewable energy facilities. The case studies that included a joint installation for shared self-consumption between companies clearly resulted in a better economic performance. This was due to both the economy of scale for larger installations and a better distribution of the produced energy between different users, maximizing self-consumption. The legislative framework in Spain, which currently applies static factors for distribution of shared-self consumption, is a barrier to further improving the economic performance of joint installations for shared self-consumption. Using dynamic factors, it has been shown that the profitability and installed capacity of joint installations would further increase.

In conclusion, this study has demonstrated that the economic performance of PV installations in industrial parks can be attractive, even in locations with very low solar radiation relative to the rest of Spain. The profitability is higher for joint installations for shared-self consumption and would be even higher if the legal framework would further facilitate the sharing of produced electricity between companies. Therefore, the integration of clean energy into the industrial sector offers an opportunity for sustainable investment, reduction of greenhouse gas emissions, and other socioeconomic benefits associated with the PV installations. The promotion of this type of installation could also be key to the viability of the sector, especially in times of economic crisis.

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