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Evaluation of the Spanish regulation on self-consumption photovoltaic installations. A case study based on a rural municipality in Spain

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ABSTRACT

In European countries, an energy transition towards renewable energies is taking place, promoting self-consumption photovoltaic systems. Some studies point out that the existing regulations and support for photovoltaic systems is still scarce in Spain. This work analyses the penetration of photovoltaic systems and their amortisation in rural areas within the Spanish regulatory framework. For this purpose, an economic decision-making method for the implementation of photovoltaic systems is proposed. This method is based on comparing the possible self-consumption scenarios included in the Spanish regulation and their payback periods. Subsequently, a rural municipality in Spain has been analysed in detail as a case study. Results show that the Spanish regulation on self-consumption does not provide an adequate profitability in rural areas, as the amortisation period with surplus sale is between 16 and 22 years. If the surplus generation is not sold, the payback rises up to 28 years. Therefore, from the economical point of view, photovoltaic generation power plants with surplus sale are more attractive than self-consumption installations, as the payback period is around 12 years. Consequently, a change in the current Spanish regulations is necessary to support individual self-consumption photovoltaic installations, to make them as profitable as photovoltaic generation power plants.

1. Introduction

In recent years, developed countries have been undergoing an energy transition, with the aim of achieving an energy model mainly based on renewable energies (REs), to solve climate change and the fossil fuels depletion. Therefore, initiatives and studies are being launched to promote the use of REs around the world [1–3]. For instance, new European regulations are being created to promote generation and self-consumption (S-C) with RE installations [4,5], as the European Directive 2018/2001/EU [6]. This directive establishes the strategic action for 2020–2030 known as "Clean Energy for All Europeans". The three main objectives of this action are improving energy efficiency, increasing the participation of the consumer in the electricity market and reducing greenhouse gasses emissions [7,8].

As a consequence of these new policies [9], the decreasing costs of RE systems [10,11] and the upward trend in electricity prices in European countries [12], the number of on-site power generation facilities mainly installed in the distribution grid using low-carbon resources, also known as distributed energy resources (DERs), has increased considerably [13]. This has encouraged the emergence of a greater number of prosumers (those who are both self-generators and consumers) [14], mainly due to the reduction of the amortisation time of these S-C installations [15]. Among these systems, photovoltaic (PV) generation power plants (GP) are the most important ones. These facilities are being increasingly promoted as a means of energy efficiency [16–19], as they are economically competitive systems [20]. For this reason, several studies have been carried out to determine the key aspects to be considered in the implementation of a S-C PV system depending on the specific constraints of each European country [21,22]. These studies consider different scenarios, such as individual installations [23] or even cooperative microgrids [24,25].

Analysing the case of Spain, a widespread installation of PV systems has been conducted over the last decades [26–28]. Due to its installation simplicity and its economic price, PV power in Spain has been increasingly used, growing almost 30% in the last year [29]. This growth is linked to the current S-C PV regulation, which has improved the payback (PB) period of this type of facilities. In this work, the potential and PB of this type of installations in rural areas under the Spanish PV S-C regulatory framework is analysed. For this purpose, an economic method for decision making in the implementation of PV systems has been proposed. This method is based on comparing the possible self-consumption

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Abbreviations

A_i	Economic compensation value (€/kWh)
BC	Billable cost (€)
cP_j	Contracted power's hourly price in billing period j (€)
CE_i	Contracted energy's hourly price in billing period j (€)
d_i	Electric demand in the ith 1-h interval (kWh)
DS	Direct sell
e_i	Surplus value in the ith 1-h interval (kWh)
ED	Electric demand
ET	Electricity tax
g_i	Energy consumption from the bulk electricity grid in the ith 1-h interval (kWh)
GEG	General electricity grid
GP	Generation power plant
I_0	Initial cost (€)
M	Photovoltaic modules number
MC_k	Monthly bill cost for month k (€)
MR	Metering equipment rental (€)
n	Billing periods number
n_K	Number of hours in month k
NB	Net billing
OL	Orientation losses
DER	Distributed energy resource
OMIE	Iberian market operator
pv_i	Photovoltaic modules' power generated in the ith 1-h interval (kWh)
P_j	jth billing period
PB	Payback (years)
Pc_j	Contracted power in billing period j (kW)
PP	Peak power (kWp)
PP_M	Photovoltaic modules peak power (kWp)
PR	Performance ratio
PV	Photovoltaic
RD	Royal Decree
RD-L	Royal Decree-Law
RE	Renewable energy
REE	Red Eléctrica de España (Spanish system operator)
S_x	xth study scenario
S-C	Self-consumption
SG	Solar generation
SL	System losses (%)
SP	Surplus
ST	Partial cost without taxes (€)
t_i	ith 1-h interval
UP	Useful power (kW)
YE	Energy cost without taxes (€)
YP	Power cost without taxes (€)

scenarios included in the Spanish regulation and their payback periods. Subsequently, a rural municipality in the Valencian Community (Spain) has been analysed in detail as a case study to validate the method. Different representative buildings of this municipality have been selected and the individual distributed S-C PV installations PB have been carefully studied. Then, the results obtained from the individual distributed installations have been compared with the scenario of a concentrated PV GP to sell energy production, considering all the associated costs of the necessary infrastructure. Based on the results, a set of recommendations for new policies are presented.

The main contributions of this paper are detailed below:

- Detailed analysis of the current Spanish regulations on S-C PV installations, with special emphasis on the economic evaluation in rural areas.
- Development of an economic assessment method for decision making when proposing the optimal generation infrastructures for rural municipalities.
- Critical evaluation of the deficient aspects of the Spanish S-C regulations, with examples of a real case study currently under development.

The rest of the paper is structured as follows. An overview of the main features of the current Spanish PV S-C regulations, and a literature review, is performed in Section 2, revealing that there is a research gap on the new regulations applied to Spanish rural areas. Section 3 shows the materials and methods, detailing the process followed for the economic evaluation of a PV generation system, considering the different S-C options established in the Spanish regulation. Section 4 presents the application of the method to a real case in a municipality of the Valencian Community (Spain). The scenarios considered in the case study allow the comparison of installing S-C PV generation systems in dwellings and building a PV GP. Section 5 presents the results obtained after analysing the different cases and the discussion of these results, as well as the limitations of this work. Finally, Section 6 shows the conclusions of the study and future research work.

2. Background and literature review

2.1. Main features of current Spanish PV S-C policies

In 2018 and 2019, the Spanish Government enacted Royal Decree-Law (RD-L) 15/2018 [30] and Royal Decree (RD) 244/2019 [31]. The sun tax established by RD 900/2015 [32], which is defined as the payment for the backup function carried out by the whole electrical system to enable the application of S-C (access tolls, system costs, and backup costs for self-produced energy) [33] was suppressed. However, the new regulation has favoured the number of private S-C PV installations [34, 35], as the previous regulation did not allow users to obtain adequate profitability from S-C PV systems [36–39]. The main changes introduced by the RD 244/2019 regulation to favour the installation of S-C PV systems are listed below:

- Elimination of the sun tax, which taxed S-C of electricity.
- Elimination of power limits for PV systems. The installed PV power can be higher than the contracted electrical power.
- New surplus (SP) compensation, which allows the prosumer to sell the produced solar generation (SG) that is not consumed, supplying it to the general electricity grid (GEG). Within this modality of SP sale, there are two possible options: net billing (NB) and direct sell (DS) [40]. NB has practically no administrative formalities to carry out and there are no taxes on the SP generated and injected into the GEG. This option is limited to installations with a capacity of up to 100 kWp. In addition, the SP is sold by the prosumer at a fixed price to the retailer in this option. This value is deducted directly from the monthly electricity bill, and the economic value of the SP cannot be higher than the monthly electricity bill. On the contrary, to benefit from DS, it is necessary to register the power plant facility as an electricity generator. This increases the administrative procedures to be completed and the grid-access charge for SP electricity, the generation tax and the taxable income must be paid. However, the prosumer receives financial compensation for SP electricity based on the electricity market price, with no constraints.
- Shared S-C is permitted, allowing communities of neighbours and associations to have collective S-C PV systems [41]. This shared S-C

has a series of limitations established in RD 244/2019, which have been updated in article 5 of RD-L 29/2021 [42].

- It is allowed to rent rooftops from third parties to generate electricity and share the profits. To this end, new methods are being developed to achieve a fair distribution of costs and benefits among the different stakeholders [43].

2.2. Previous studies on current Spanish PV S-C policies

Following the regulatory change in Spanish PV S-C made between 2018 and 2019 [30,31], different papers have analysed the installation of solar PV panels for S-C in different scenarios. The existing contributions under this new Spanish regulatory framework are commented below.

On the one hand, in urban residential sector, the power of optimal S-C PV installations has been studied in Ref. [44]. This study shows that for most dwellings, commercial kits of 1.5–2 kWp are the most profitable option in the short term, minimising the initial investment. On the other hand, the suitable power is related to the annual electric demand (ED), as reported in Ref. [45]. This work reflects that S-C PV installations of less than 5 kW are the most cost-effective, but only if the annual consumption is higher than 2000 kWh/year. Moreover, the profitability of the residential sector has also been studied as a function of the number of residents in Ref. [46]. In case that the number of residents increases from 1 to 4, the PB period decreases, thanks to more flexible ED management, which allows a higher S-C rate. Likewise, there are also studies in the urban residential sector that analyse residential buildings [47]. They show how the limitations of current regulations do not make the implementation of a collective S-C PV system attractive.

In the same way, the educational and office sector has been analysed [48]. Due to the fact that the surface areas of these buildings allow higher capacity installations, the DS option is beginning to have greater relevance, due to its greater profitability for capacities beyond 50 kWp. However, for power ratings below 50 kWp, the profitability of both options is very similar, with a clear advantage for the NB option due to its lower administrative procedures. As for the industrial sector, there is great heterogeneity within the sector itself, but most of the energy generated is self-consumed. In this context, a method has been developed to obtain the useful power (UP) to be installed to minimize its PB in Ref. [49].

Likewise, there are studies comparing the impact of the new Spanish regulation on the three main sectors (residential, commercial and industrial) [40]. They show that the residential sector is the one with the lowest profitability. In this sector NB is usually the most appropriate option because of its administrative simplicity, but it limits the monthly earnings of prosumers. There is a clear tendency to recommend the NB option in the urban residential sector. In addition [50], shows the PV potential that could be obtained from the building's roofs (residential, commercial and industrial), but subsidies should be earmarked to make them economically attractive in most cases.

Finally, the establishment of energy communities has also been studied within the framework of the current Spanish regulation. In Ref. [51], the authors analyse how energy communities are increasingly present in the Spanish territory due to their advantages. However, high administrative barriers are limiting their development potential. To obtain the optimal installations for each Spanish region, a computational techno-economic optimization tool is used in Ref. [52]. Regional results showed that S-C is cost-effective in all the territory, but specific policies oriented to facilitate the deployment of S-C while ensuring fair conditions to small and new actors in the power system are needed. The present electric cooperatives in Spain are analysed in Ref. [53], which are a minority and are currently unable to compete at the national level with the large electric companies. Therefore, that work presents a series of recommendations for the creation of new electric cooperatives, as well as improvements in the current regulations. Due to the importance of the conditions in the location where a PV GP is built, a method to detect the optimal PV GP location has been developed in Ref. [54]. With this method, it is possible to obtain the location for the PV GP in the energy community that minimizes the PB, which might not be economically profitable.

In conclusion, the current regulation allows greater profitability of S-C PV installations than the previous regulation, but it still needs to be improved. These improvements would further promote the energy transition in Spain, as it is a country with ideal climatic conditions for the implementation of PV systems [55,56].

After analysing the studies carried out under the current Spanish PV S-C regulation, the assessment of the impact of the regulation on rural areas has been identified as a clear research gap. Although these areas do not have the same population density as urban areas, Spain has a large number of rural municipalities. In addition, the rooftops/inhabitant ratio is higher than in urban areas (due to the presence of single-family dwellings instead of residential buildings), which allows a greater number of S-C PV installations. Due to its great interest and the novelty that it entails, this work evaluates the potential of this type of installations in rural areas, as well as its amortisation, under the Spanish regulatory framework for S-C.

3. Materials and methods

This section describes the method used for the economic evaluation of PV generation systems implementation, considering the different S-C options established in RD 244/2019. A general scheme of the presented method is shown in Fig. 1.

Firstly, a detailed study of the solar PV installation for S-C of a dwelling must be carried out to obtain the economic data of the annual energy costs. The economic data of the annual energy costs are compared for four scenarios, as shown in Fig. 2:

- S_0: Without PV installation (base scenario).
- S_1: With PV installation without sale of SP.
- S_2: With PV installation and sale of SP in NB modality.
- S_3: With PV installation and sale of SP in DS modality.

The equations used to calculate the technical and economic parameters are described in the next subsection. Once the annual economic savings have been obtained, the different PB periods of the PV installation in scenarios S_1, S_2 and S_3 are calculated.

Subsequently, the same study must be carried out for several dwellings of a municipality, to extrapolate the results to an entire municipality with high accuracy. Once the total investment that the individual installations of the S-C PV systems for the entire municipality would entail has been determined, a concentrated PV panels installation in a PV GP that could be projected with the same investment can be defined. The PB of this PV GP can be calculated to compare both options under the current Spanish regulation.

3.1. Dwelling study

The method used to compare the possible PV S-C scenarios for a dwelling in Spain is detailed in this section. The calculation scheme is shown in Fig. 3.

Firstly, it is necessary to record the annual hourly ED of the dwelling, to obtain the annual electricity billing. The hourly billing term is obtained from the Spanish system operator's website (Red Eléctrica de España, REE), as these tariffs are regulated [57].

Secondly, the area available on the plot of the dwelling for the installation of S-C PV panels must be obtained, which allows the calculation of the PV PP to be installed in the dwelling. The corresponding loss correction factor must be applied to this PP to determine the UP of the S-C PV installation. According to literature a performance ratio (PR) of 75.80% is assumed in this study [58–60]. This PR considers all the losses associated with the PV generation system, except for losses

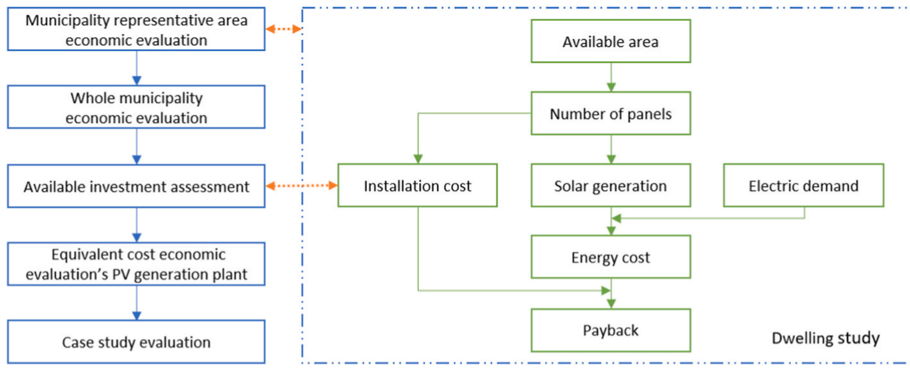

Fig. 1. Methodology scheme.

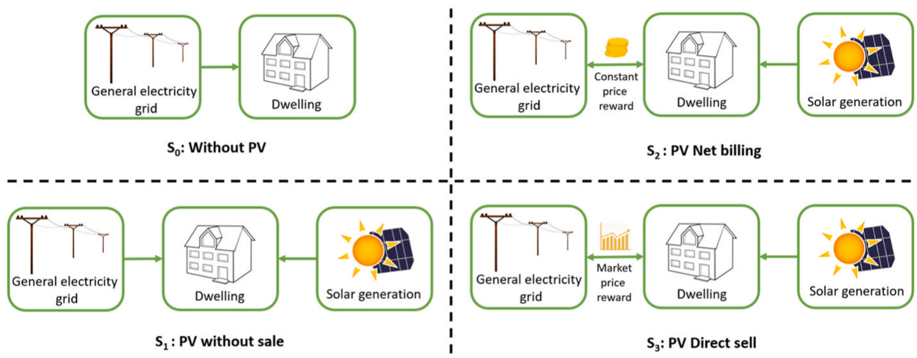

Fig. 2. Base scenario and PV self-consumption scenarios.

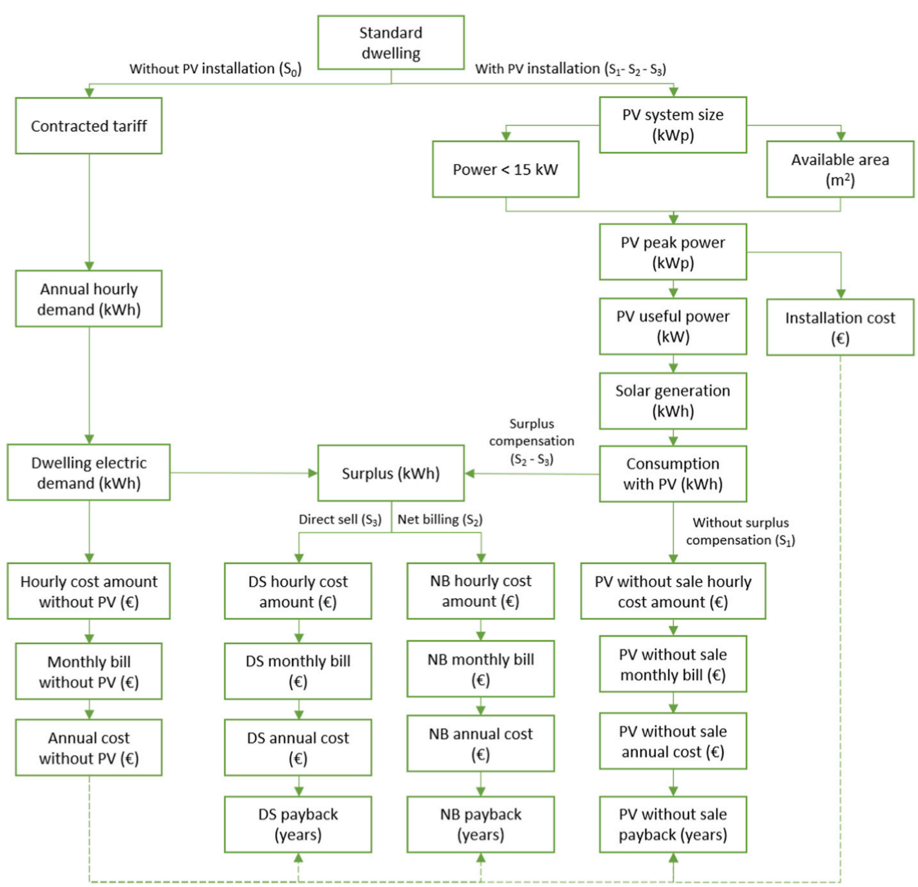

Fig. 3. Calculation scheme.

related to the panels orientation. The orientation losses are obtained by modelling the facilities in the PVSyst software [61]. Therefore, the total losses of the system are given by equation (1).

$$SL = (0.758 \cdot (1 - OL)) \cdot 100 \tag{1}$$

Where SL: system losses (%)

OL: orientation losses

The UP of the S-C PV system is calculated using equation (2).

$$UP = M \cdot PP_M \cdot SL \tag{2}$$

Where M: PV modules number.

PP_M: PV modules PP (kWp)

Likewise, knowing the PP, a factor of 1.69 €/kWp [40] is used to obtain the cost of a S-C solar PV installation in a dwelling. The initial cost (I_0) of the S-C PV installation is given by equation (3).

$$I_0 = 1.69 \cdot PP \tag{3}$$

Thirdly, the hourly SG of a S-C PV installation in the same area is recorded for a period of one year. Although the value of the SG could be obtained from the values of the global solar radiation of the area and the total power of the S-C PV installation, the available databases with the values of the global solar radiation in rural areas are substantially outdated. Therefore, it is mandatory to carry out a specific registration of the SG.

Once all the characteristic data of the PV installation are available, it is possible to establish the method for calculating the economic cost of the different PV S-C scenarios (Fig. 2) allowed by Spanish regulations.

3.1.1. Cost determination without S-C PV installation (S_0)

The base scenario is studied considering that the dwelling does not have a S-C PV installation (S_0). This is not considered among the possible solutions within the S-C regime, but it is necessary to include it as a base scenario to analyse and compare the advantages of the other cases.

Once the ED and the annual hourly billing of the dwelling is known, it is possible to know the amount that the consumer will be billed in each hourly period without a PV installation by following the procedure described below. To establish the calculation procedure, the current regulations that detail the billing model have been taken into account [62,63].

Over a calendar year, the time is divided into 8760 1-h intervals, t_i for $i \in [1; 8760]$, which belong to a billing period P_j for $j \in [1; n]$. In each interval, the ED of the installation has a value d_i, which coincides with the energy consumption from the GEG g_i. Therefore, for this first scenario $g_{1i} = d_i$. In each billing period, there is a contracted power Pc_j which represents the maximum possible ED from the grid and an hourly price cP_j is established for these periods. Consequently, $g_{1i} \le Pc_j \; \forall \; t_i \in P_j$. On the other hand, as regards the energy consumption, each interval t_i has an energy price CE_i. With these concepts, the partial cost without taxes (ST) is obtained as the sum of the energy costs (YE) and power costs (YP) for a whole year, using equations (4)–(6).

$$YE = \sum_{i=1}^{i=8760} CE_i \cdot g_{1i} \tag{4}$$

$$YP = 8760 \cdot \sum_{j=1}^{n} Pc_j \cdot cP_j \tag{5}$$

$$ST = YE + YP \tag{6}$$

In these equations, n = 3 for the case of the Spanish regulation in force, since the peak, shoulder and valley billing periods are used.

The electricity tax (ET) is added to this cost, which is calculated as shown in equation (7).

$$ET = ST \cdot 1.05113 \cdot 0.04864 \tag{7}$$

Finally, the monthly rental of the metering equipment (MR) is added to these concepts, and the Value Added Tax (21%) is applied to the total, so that the billable cost (BC) for this first scenario can be obtained by means of equation (8).

$$BC_1 = (ST + ET + 12 \cdot MR) \cdot 1.21 \tag{8}$$

Since electricity billing in Spain is done monthly, the value of the monthly bill (MC_k) must be obtained using equation (9). This equation will allow the comparison of a single invoice from different scenarios.

$$MC_{1k} = \left(\left(\sum_{i=1}^{n_k} g_{1i} \cdot CE_i \right) + n_k \cdot \left(\sum_{j=1}^{n} Pc_j \cdot cP_j \right) + ET + MR \right) \cdot 1.21 \tag{9}$$

Where n_k is the number of hours in month k.

Finally, once the monthly bills are known, it is possible to obtain the cost of energy for a whole year BC_1 that a consumer should pay without a S-C PV installation. This cost coincides with that obtained from equation (8).

Therefore, the purpose of equation (8) is obtaining the total economic cost for one year, which allows a later comparison of profitability in a simple way. Conversely, equation (9) allows the comparison of this scenario with others for each bill independently, so that it is possible to analyse the differences in each specific month.

3.1.2. Cost determination with PV installation without SP sales (S_1)

To determine the costs without selling SP from a S-C PV system (S_1), it is also necessary to know the annual hourly SG. This is a unidirectional case, i.e. it is based on consuming the SG produced by the PV system when it is available, instead of using the GEG. There may be periods of zero consumption from the GEG, but no power is ever supplied to the GEG.

Firstly, it is necessary to carry out an hourly energy balance for this second scenario, checking the availability of SG. If there is SG for a given period, this will be used for S-C, and it will not be necessary to consume this energy from the GEG. If the SG is higher than or equal to the ED of the dwelling, the energy consumption from the GEG, for that period, will be null. The value of the ED for each hourly interval t_i, in a S-C regime without sale of SP is calculated using equation (10).

$$d_i = g_{2i} + pv_i \tag{10}$$

Where pv_i is the self-consumed power (kW) from the PV modules, which must fulfil $pv_i \le d_i$.

Secondly, it is possible to determine the energy cost for a whole year with a S-C PV system without selling SP. To do this, the same procedure is followed as in scenario S_0. Only the value of the demand curve from the GEG is modified according to equation (10), with the same price applied to each hourly interval as in the previous section.

The annual amount that the consumer will be billed if they have a PV system without SP sales and the monthly billing, for this second scenario, are given by equations (11) and (12), respectively:

$$BC_2 = \left(\left(\left(\sum_{i=1}^{i=8760} g_{2i} \cdot CE_i \right) + 8760 \cdot \left(\sum_{j=1}^{n} Pc_j \cdot cP_j \right) \right) \cdot (1 + 1.05113 \cdot 0.044864) + 12 \cdot MR \right) \cdot 1.21 \quad (11)$$

$$MC_{2k} = \left(\left(\left(\sum_{i=1}^{n_k} g_{2i} \cdot CE_i \right) + n_k \cdot \left(\sum_{j=1}^{n} Pc_j \cdot cP_j \right) \right) \cdot (1 + 1.05113 \cdot 0.044864) + MR \right) \cdot 1.21 \quad (12)$$

Again, equation (12) will facilitate the comparison of single invoices from this scenario with others. Finally, in order to be able to economically compare all possible S-C regimes, the simplified PB is calculated, based on the I_0 of the installation, given by equation (13).

$$PB_2 = \frac{I_0}{BC_1 - BC_2} \quad (13)$$

It is worth mentioning that despite being a method that does not consider inflation, nor any profit or loss that may arise after the recovery period, it shows the economic difference between the different cases with the conditions of the regulation in force in Spain in a simple and clear manner.

3.1.3. Cost determination with PV system and sale of SP

If a prosumer uses the PV S-C system with sale of SP, there is a case with bidirectional energy exchanges. If there is an hourly interval where the SG is higher than the ED of the dwelling, the SP is sent to the GEG. In those time intervals where the ED is higher than or equal to the SG, part or all of the necessary energy will be consumed from the GEG, depending on whether there is SG or not, so the equations of the previous case can be applied in those time intervals.

Under these conditions, the first step consists of calculating the SP values at each hourly interval throughout the year. For this purpose, the difference between ED and SG is checked, with the SP being the difference in the periods where the SG of the S-C PV system is higher than the ED of the dwelling. The SP in each time interval, for this scenario, is given by equation (14).

$$d_i + e_i = g_{3i} + pv_i \quad (14)$$

Where $e_i \geq 0$ is the SP generation from PV panels fed into the GEG, and $g_{3i} \geq 0$ is the energy imported from the GEG. Therefore, in scenarios with a PV installation and sale of SP, during certain intervals t_i some energy may be supplied to the GEG.

Secondly, it is necessary to know the payment to the prosumer in each hourly interval t_i in which energy is being fed into the GEG. To do this, it is necessary to distinguish between NB or DS.

3.1.3.1. NB S-C modality (S_2). In the NB case (S_2), the prosumer will receive financial compensation for each kWh, at a fixed price. In other words, the retailer will establish the amount that will be paid for the SP, regardless of the time period t_i. Currently, the mean value offered by the electricity companies as a compensation for the SP in Spain is 0.0338 €/kWh [47]. Therefore, the value of the amount that will be paid to the prosumer monthly, under NB contracts, is given by equation (15).

$$NB_k = \sum_{i=1}^{n_k} 0.0338 \cdot e_i \quad (15)$$

On the other hand, it is necessary to consider that in NB case, it is not possible to obtain an economic benefit at the end of the month. That is, the monthly bill cannot be negative, since this would imply that the electricity company would pay the consumer at the end of the month. Therefore, knowing the monthly cost in the case of having a S-C PV installation, given by equation (12), the monthly cost under NB contracts, will be given by equation (16).

$$MC_{3k} = \begin{cases} MC_{2k} - NB_k & \text{if } NB_k \leq MC_{2k} \\ 0 & \text{if } NB_k \geq MC_{2k} \end{cases} \quad (16)$$

Knowing the monthly amount that will be billed to the prosumer, the annual cost of electricity under NB modality is given by equation (17).

$$BC_3 = \sum_{k=1}^{m} MC_{3k} \quad (17)$$

Where $m = 12$ is the total number of months in a year.

Finally, the simplified PB is calculated for economic comparison. The simplified PB for NB is given by equation (18).

$$PB_3 = \frac{I_0}{BC_1 - BC_3} \quad (18)$$

3.1.3.2. DS S-C modality (S_3). In case of DS (S_3), the prosumer will receive an economic compensation for each kWh. This value is different for each t_i and it is established by the Spanish market operator, Operador del Mercado Ibérico de Energía (OMIE). This compensation is published on REE's website [64] for each hourly interval. In this case, it must also be considered that Spanish regulations establish a 7% tax on the electricity supplied, as well as a grid-access fee on SP electricity of 0.5 €/MWh. Therefore, the value of the monthly amount that will be paid to the prosumer under DS contracts will be obtained by means of equation (19).

$$DS_k = \sum_{i=1}^{n_k} \left(\left(0.93 \cdot A_i - \frac{0.5}{1000} \right) \cdot e_i \right) \quad (19)$$

Where A_i is the value of the economic compensation per kWh, established by OMIE.

However, under DS modality, it is possible to obtain a benefit at the end of the month. In other words, the bill can be negative, with the prosumer receiving this financial compensation. Therefore, following the same procedure as in the previous case, the monthly amount, the annual amount and the simplified PB under DS mode will be given by equations (20)–(22) respectively.

$$MC_{4k} = MC_{2k} - DS_k \quad (20)$$

$$BC_4 = \sum_{k=1}^{m} MC_{4k} \quad (21)$$

$$PB_4 = \frac{I_0}{BC_1 - BC_4} \quad (22)$$

4. Application of the proposed method to a rural municipality

This study was carried out in the municipality of Aras de los Olmos. It has a total of 374 inhabitants, as indicated in the Municipal Data Bank of the Generalitat Valenciana [65]. It is located in the northwest of the province of Valencia (Valencian Community, Spain), bordering on the north with the province of Teruel (Aragon, Spain), and on the west with the province of Cuenca (Castilla La Mancha, Spain). The selection of this municipality in the Valencian Community has been made based on the following reasons:

- The municipality has assumed the responsibility of becoming self-sufficient in the coming years, due to the numerous problems of electricity supply and power quality because of the location of the municipality on the border of the Valencian Community. It is located at the end of the distribution line, which leads to a significant economic loss for the businesses that depend on the electricity supply, as well as continuous problems and power outages in dwellings.
- The location of the municipality presents ideal characteristics for RE systems implementation. On the one hand, it has a large area of free roofs for the installation of S-C PV systems, as well as unused plots that could be used for the installation of a PV GP. On the other hand, the climatology of Mediterranean areas is very favourable for PV systems due to the high number of sunshine hours.
- The municipality has its own electricity distribution company, which simplifies the administrative procedures.
- The authors have been working on various projects in the municipality related to high and low voltage installations. As a result of this work, an electricity consumption historic record has been logged, as well as SG curves from some existing PV installations.

For all these reasons, the municipality of Aras de los Olmos has been selected to perform a critical evaluation of the economic feasibility of a widespread S-C PV installation in a rural area under the Spanish regulation. As a result of this study, the usefulness of the new regulation in areas that present ideal conditions for the installation of S-C systems will be verified. In addition, the obtained results will be compared with the possibility of designing a PV power plant close to the municipality with the same initial investment.

For this purpose, a first study of distributed individual S-C PV installations is carried out in a representative area of the municipality. This area has been selected considering the number and use of buildings in the whole municipality. The ratio of buildings in which it is possible to install PV panels in the studied area for S-C is obtained. Subsequently, these results are extrapolated to the whole municipality, obtaining the total budget that the residents of the municipality would have to invest. With the total budget, the feasibility of designing and building a PV GP, dedicated exclusively to the sale of the energy produced, is studied. A comparison of both RE generation strategies (individual distributed S-C PV installations and concentrated PV panels installation in a PV GP) of PV production is finally performed to draw the final conclusions.

4.1. Dwellings study in a representative area of the municipality

The study carried out using the presented methodology is shown below. A total of 69 representative land plots in the municipality of Aras de los Olmos have been analysed. These plots represent 6.84% of the built-up area of Aras de los Olmos, including buildings of various types, representative of the whole municipality. The set of selected plots is shown in Fig. 4. This figure shows the cadastral references of the plots on the left and a satellite image with the proposed layout of PV solar panels for individual S-C in the roofs on the right.

Firstly, those plots that are not catalogued as dwellings have been discarded. That is, plots without buildings or registered as ware dwellings or car parks are not considered. In addition, dwellings where the installation of PV solar panels for S-C is not possible have also been excluded. The reasons for exclusion are:

- North, north-west or north-east roof slope, as the installations have high slope losses (the PR is too low).
- Presence of shadows, due to the fact that the roof has a lower height than other adjacent buildings.
- Insufficient physical space for the installation.

Secondly, the number of dwellings in which it is possible to install PV panels for S-C is determined, and the number of panels that can be installed in each one is determined. The installed PP is then known, and

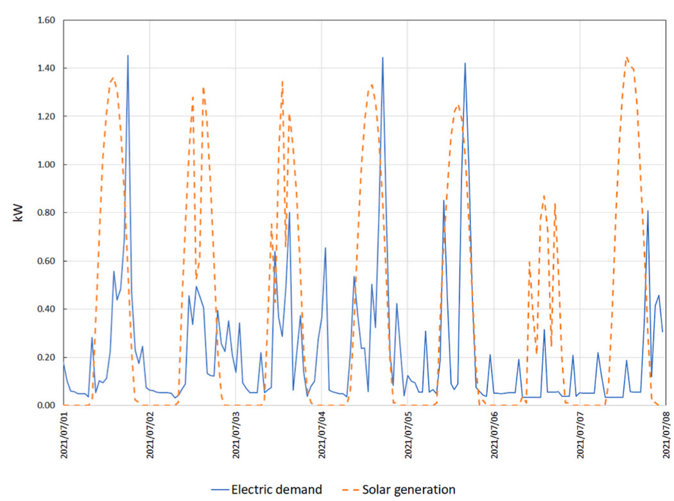

Fig. 5. Typical dwelling's electric demand and solar generation.

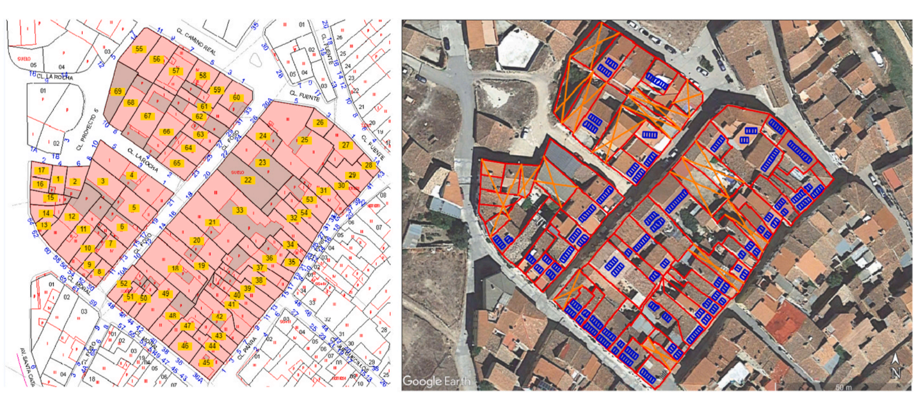

Fig. 4. Representative plots. Left: Cadastral reference. Right: Satellite image showing solar panels layout.

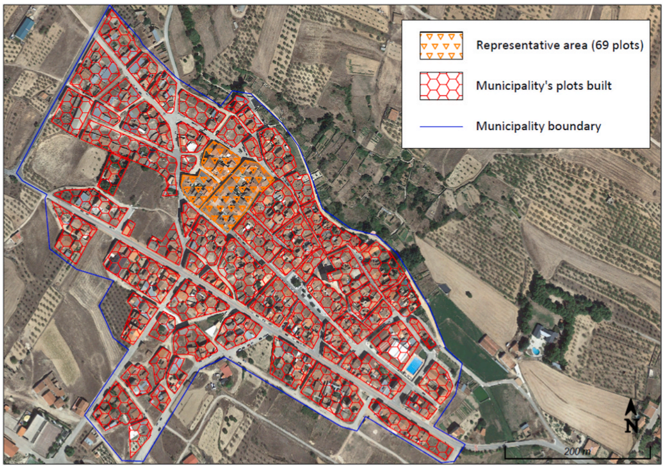

Fig. 6. Aras de los Olmos (Valencian Community, Spain).

equations (2) and (3) can be used to obtain the UP and the investment needed for each installation, respectively. The installations are planned with 330 Wp PV modules, with measures of 1 × 1.9 m^2.

Finally, knowing the tariffs contracted by the owners, the annual consumption of the dwellings and the expected SG in each dwelling, the proposed methodology is applied. The PB of the PV installation is thus obtained for all possible modalities of S-C currently available in Spain. Characteristic data of each studied plot, as well as the PV S-C installation that could be installed, are listed in Appendix 1, Table A1. 1. On the other hand, the annual economic results, obtained from equations (8), (11), (17) and (21), and the PB of the PV S-C installations projected for the different scenarios, calculated with equations (13), (18) and (22) can be found in Appendix 1, Table A1. 2.

For this case study, data from 2021 have been used, as there are two important characteristics of that period to analyse the current Spanish regulations. On the one hand, from 2021 June 1st all existing tariffs below 15 kW were unified into the 2.0. TD single tariff [66]. Therefore, the economic impact of this change in the regulation can be analysed from the results. On the other hand, the impact of the increase in the electricity price that has been taking place since the end of 2021 throughout Europe, and particularly in Spain, can be analysed.

Finally, as a representative example, Fig. 5 shows the ED and PV SG curve for a typical dwelling. As shown in Fig. 5, in rural areas, there is a significant ED towards the last hours of the day, when SG is low or non-existent.

4.1.1. Study in the whole municipality

After a detailed analysis of a representative area of Aras de los Olmos, the extrapolation of these results to the whole municipality is performed. Fig. 6 shows the area of the whole municipality under study, in which the installation of individual distributed PV systems for S-C is considered.

For this case study, the respective ratios ED/area = 31.24 W/m^2 and SG/area = 8.26 W/m^2 have been considered. These values have been obtained from the studied area with 69 plots shown in Fig. 4. Table 1 shows the graphical surface, ED and total SG of the municipality considering all the individual PV installations, after applying the indicated ratios. SG equals UP of the individual distributed PV systems. The total investment that should be made is also indicated. This amount is obtained as the sum of the cost of all the individual PV S-C generation systems planned for the entire municipality. A map viewer has been used to obtain the total area of the municipality under study.

Table 2 shows the most representative PB statistics. These data have been obtained by extrapolating the data from the studied area to the whole municipality. The graphical representation of the PB value for the different S-C options using a box-and-whiskers diagram is shown in Fig. 7.

Table 1
Results extrapolated to the whole municipality Aras de los Olmos.

Graphic area (m^2)	Electric demand (kW)	Peak power (kWp)	Useful power (kW)	Total investment (€)
113,774.00	3554.00	1481.30	939.81	2,503,401.82

Table 2
Payback (years) statistics of the extrapolated results to Aras de los Olmos in each scenario.

Statistics concept	PV without sale (S_1)	PV Net billing (S_2)	PV Direct sell (S_3)
Maximum	40.35	36.90	32.75
Average	27.99	21.71	16.27
Minimum	20.26	16.50	12.82
Standard error	0.76	0.49	0.43
Median	26.73	21.23	15.86
Standard deviation	5.07	3.28	2.84
Sample variance	25.75	10.73	8.05
Range	20.10	20.40	19.93

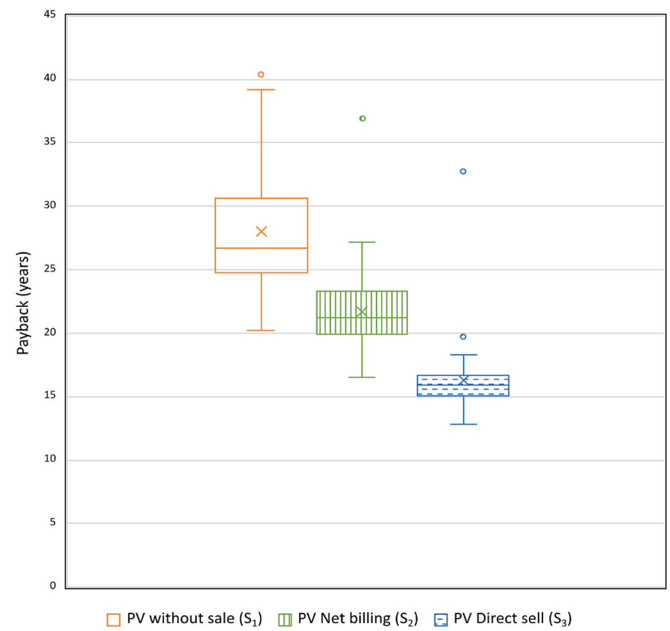

Fig. 7. Payback box-and-whisker diagram of the extrapolated results to Aras de los Olmos.

Table 3
Concentrated PV generation plant characteristic data and comparison with the set of individual distributed PV systems for self-consumption.

Characteristic concept	Concentrated PV generation plant	Percentage value with respect to individual distributed self-consumption PV systems
Total available investment budget (€)	2,503,401.82	100.00%
PV generation plant economic ratio (€/Wp)	1.22	72.19%
Peak power to be installed (kW)	2053.83	138.66%
Performance ratio (%)	75.80	118.22%
Useful power (kW)	1556.80	165.65%

4.2. Study of an equivalent PV GP

An alternative to individual S-C PV installations is presented in this section, in order to compare the obtained results. In this case study, the initial objective is to reduce the PB of the distributed PV installations. For this purpose, an initial budget equivalent to the sum of all the investments needed for the individual S-C PV systems, shown in Table 1, is considered. Due to the legal limitations and increased legal formalities involved in the creation of an energy community, the development of a grid-connected PV GP close to the municipality is proposed.

First of all, it is necessary to calculate the associated costs of a concentrated PV GP. Although a factor of 1 €/Wp [40] is used in the literature and in practice for generating installations, it must be taken into account that this ratio only refers to the PV plant. Therefore, it is also necessary to include the cost of acquiring the plot, the geotechnical study, the costs of drafting and construction management by a qualified technician, the construction of the transformer station, the electrical distribution line and the associated administrative procedures. These costs, taking as a reference a 756 kWp PV GP in whose design the authors have participated, can be seen at Appendix 2, Table A2. 1. In the same table (Appendix 2, Table A2. 1), it can be seen that including all the elements associated with the construction of the PV GP, the ratio increases from 1 €/Wp to 1.22 €/Wp in rural areas.

Table 3 shows the total power that could be produced in a PV GP with the same budget that would be used for the installation of individual distributed PV S-C systems in the dwellings of the municipality of Aras de los Olmos. To obtain the UP of the GP, no orientation losses have been considered in equation (2), as the PV modules can be installed facing south. Likewise, Table 3 shows a comparison of the characteristic data obtained from the concentrated PV GP with the values from the individual distributed S-C PV systems in the whole municipality, expressed in percentage. This comparison shows that, with the same initial economic investment, the obtained UP is 1.65 times greater than in individual installations. This is due to both the optimization of the panels orientation and the lower specific cost of the installation in €/Wp.

In this case, the entire electricity production is sold. Therefore, the calculation method to obtain the PB of the installation is identical to the case of a PV installation with sale of SP at a variable price, i.e., DS modality. Consequently, equations (19), (20), (21) and (22) are used. In this particular case all production is imputed as SP as there is no ED.

Considering the respective electricity taxes and the network access fee, the PB of the installation in this case, applying equation (22), is 11.7 years.

5. Results and discussion

The results obtained after analysing the different real cases detailed in previous sections, as well as their discussion, are presented in this section.

Firstly, it is shown that for a rural area located on the east coast of Spain, the installation of S-C PV panels reduces the monthly cost of the electricity bill of a dwelling. This fact can be seen in Fig. 8, which shows the monthly amount of the electricity bill for one year under the four studied scenarios. According to this figure, the monthly bill without a S-C PV installation is always the highest one.

However, the fact of reducing the monthly bill is not a sufficient reason to make the decision of installing S-C PV panels. The current regulation on S-C must be analysed to calculate the PB of the installation. As a result of the developed study, it must be highlighted that the current regulation in Spain (RD 244/2019) involves a significant improvement in case of installing S-C PV panels compared to the previous regulation (RD-L 15/2018). This is shown in Table 2, by comparing the PB of PV installations with and without the possibility to sell SP (with the DS or NB option). This analysis corresponds to the comparison of the previous regulation with the new one. The DS and NB modalities reduce the average PB by 11.72 years and 6.28 years respectively. Furthermore, the average PB value of 27.99 years for the case of not selling SP makes it clear that the old Spanish regulation did not stimulate the installation of S-C PV panels, since in most cases it was not possible to recover the initial investment before the end of the useful lifetime of the equipment.

Secondly, there is extensive literature that recommends NB option over DS [44–47]. This is based on the fact that the installation of S-C PV panels is amortised in a shorter period of time and the administrative procedures are less time-consuming. Although it is true that under NB modality the administrative procedures are minimal, Table 2, shows that the average PB for NB is 21.71 years, compared to 16.27 years for DS. This is mainly due to two factors. On the one hand, retailers offer a real average fixed price per kW around 0.038 €/kWh [47], which is lower than the 0.05 €/kWh offered on the websites of the large electricity companies. On the other hand, if a prosumer chooses the DS option, the amount paid for the SP is variable, but proportional to the market energy price. Therefore, with the increase in the electricity price experienced from the second half of 2021, a higher amount of money is also paid for the SP produced. In addition, prosumers have the possibility to receive money at the end of the month in case the SG exceeds their own consumption. In other words, with the increase in the electricity price, the DS option starts to become more profitable, as shown in Figs. 8 and 9.

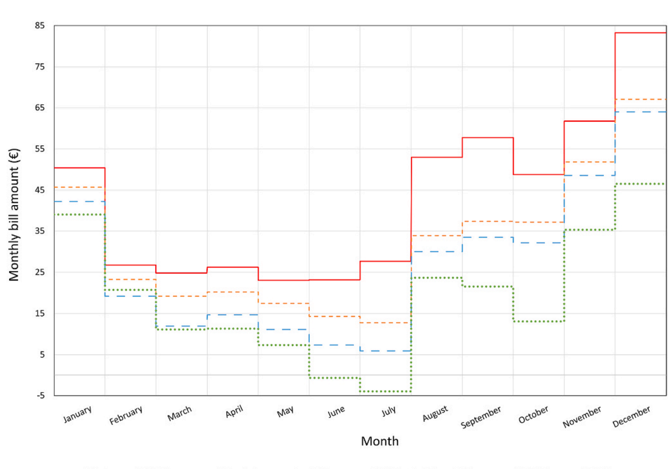

Fig. 8. Dwelling's monthly bill for the four scenarios studied.

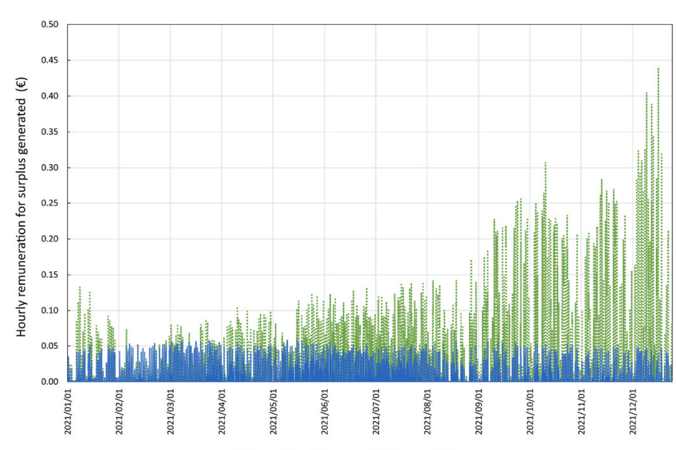

Fig. 9. Amount paid for surplus in net billing and direct sell modalities of a prosumer.

Fig. 9 shows that from November 2021 the difference between the amount paid under NB and DS options has increased considerably. This date coincides with the increase in the prices of gas and electricity across Europe [67,68]. This leads to a reduction in the amount of the monthly electricity bill, as shown in Fig. 8. In addition, the DS option has a considerable advantage in summer months. This is due to higher irradiation (and therefore higher SG), which allows prosumers to receive financial compensation from the electricity company. Although this is not a generalised result for all dwellings, it is an important factor to take into account.

On the other hand, the existing literature [69–72] and the data provided by the companies, estimate the PB for a concentrated PV panels installation in a PV GP around 6–8 years or even lower. It is observed that this type of installation has certainly a lower PB than individual distributed S-C installations in dwellings. However, the PB for this case study is close to 12 years. This is because other costs associated with the PV GP have been considered, as well as the losses associated with the system, as opposed to other works, to obtain more realistic results. Therefore, using the proposed methodology the PB of the PV GP is around 8 years, in case that all system losses are neglected, i.e., assuming a PR of 100%. It would also be necessary to consider only the cost of the PV GP and not all the other costs considered in the general case. This shows that the data publicly displayed in some other studies only refer to an ideal case, which is far from reality.

As a result of this research work, the following individual actions are proposed to reduce the PB of S-C PV installations in dwellings, to stimulate their installation:

- Since the greatest economic savings are achieved by directly consuming the energy produced by S-C solar panels, it is necessary to adapt the consumption habits of users to the instantaneous solar production. That is, it is necessary to minimize the SP generated and injected into the GEG. In other words, in addition to the regulations, the consumer also plays a crucial role in the amortisation of the installation [73].
- In recent months there has been a clear discouragement of the combustion vehicle in Europe, in favour of the electric vehicle. This means that the GEG must be extended to guarantee the electricity supply for these new loads, and this gives the PV S-C installation a greater importance. The electric vehicle is equivalent to having a battery system. Therefore, the electric car can be considered as an extra load in the dwelling, which, if its state of charge is well managed, would enable a more appropriate use of the solar PV S-C installation.

On the other hand, a series of government actions are also needed to increase the stimulation in the installation of PV panels for S-C, such as the ones listed below:

- Eliminate the monthly economic limitation of the NB option. Residents would get a higher return from the S-C PV installation in a simple way.
- Establish a series of ranges for the fixed price paid in the NB mode, based on the actual market price.
- Reduce and facilitate the formalities of the DS option.
- Eliminate bureaucratic restrictions for the implementation of an energy community. At present, it is necessary to fulfil a series of requirements that do not make its implementation possible in almost any environment. However, the implementation of an energy community would allow many inland municipalities to be self-sufficient at peak SG times and even obtain an economic benefit from the sale of the SP generated.

With these recommendations, the creation of new prosumers would be encouraged since Spain has very suitable climatic conditions [74].

Finally, it should be pointed out that this work has a series of limitations, which are detailed below:

- This work presents an overview of possible S-C solutions and their economic profitability in a rural municipality in eastern Spain. Therefore, the conclusions of the case study cannot be extrapolated to an urban area, with higher ED and greater diversity of consumption. Furthermore, in urban areas, the cost of land for the installation of a PV GP is much higher, and even impracticable due to lack of space in most cases.
- Although the results cannot be directly extrapolated to a rural area with different solar radiations, the presented methodology can be applied to any case with the detailed data, provided that it has a regulatory framework similar to that of Spain.
- The increasing trend in electricity prices must be considered. This fact improves the PB, making it possible to obtain an economic profitability of the S-C PV installations in a shorter period. The results of the case study prove some flaws of current regulations, but the quantitative results can vary, as noted above.

6. Conclusions

In this study, a critical economic evaluation of S-C PV installations in rural areas has been realized based on the current Spanish regulation (RD 244/2019). For this purpose, an economic evaluation method of S-C PV installations has been proposed for decision making in their implementation, which can be applied in any area of the Spanish territory or other countries with similar S-C regulations. Subsequently, this method has been applied in a rural municipality in the Valencian Community (Spain), which has numerous rooftops available for the installation of individual S-C PV systems, flat areas for the installation of a PV GP, and many hours of sunshine per year. The results obtained can be extrapolated to similar areas.

The different cases of S-C currently possible in Spain have been studied: with PV installation of S-C without sale of SP, with PV installation of S-C and sale of SP under NB modality and with PV installation of S-C and sale of SP under DS modality. In addition, all scenarios have been compared with a base scenario without PV installation. To this end, a total of 69 representative dwellings of a municipality have been studied, with the aim of extrapolating these results to the whole municipality. Subsequently, the possibility of pooling the investment of all the distributed PV installations for the construction of a concentrated PV GP has been analysed and its PB has been calculated. All this has been analysed over a period of time that allows the analysis of the regulatory change in the electricity tariffs, applied from 2021 June 1st.

The results of this study show that the current Spanish regulation does not make the installation of PV panels for S-C in rural dwellings attractive, as the PB period is still too high. However, due to the current electricity prices and their upward trend, three interesting results have been observed. First, in case of an individual S-C PV installation, the SP sale allows a reduction of the PB in all cases. On average, the PB is reduced from 28 years (if the SP is not sold) to 16–22 years (if the SP is sold). Secondly, the upward trend in the electricity price results in shorter PB periods for the S-C PV installation under DS contracts (16.27 years). This makes DS a more interesting choice than NB (21.71 years), despite the administrative procedures. The average PB under the NB modality is 33.44% higher than under DS. Thirdly, a much more attractive alternative results to be the energy community. This option consists of a group of neighbours that build a concentrated PV GP with the same economic investment, with the aim of selling all the production, without taking advantage of the S-C regulations. In this case, the PB of the installation is reduced to less than 12 years.

Even though the regulation of PV S-C in Spain has been improved with RD 244/2019, this study has shown, by analysing the case of a real municipality with suitable characteristics for the installation of S-C PV systems, that it is still not economically profitable in the medium term. Therefore, a series of modifications and improvements in Spanish regulation are still necessary to support individual S-C PV installations, to make them as profitable as PV GPP. Among these changes, the following ones should be highlighted:

- Eliminate the monthly economic limitation under NB.
- Establish a series of ranges for the fixed price paid in the NB mode, based on the actual market price.
- Reduce and facilitate the formalities of the DS option.
- Eliminate bureaucratic restrictions for the implementation of an energy community.

As future research lines, the inclusion of batteries or electric vehicle as an energy storage system, instead of selling SP generation, is an important parameter to be studied. A deeper study of the electricity tariffs offered by the retailers is also an interesting option to be considered, since in the last months, a great variety of offers are being introduced. In this context, only the tariffs established by REE [57] have been studied, which are the most typical ones, especially in rural areas. Additionally, it would be interesting to explore the effects of subsidies on the studied parameters. Likewise, energy communities are also an interesting field of study where new research works are being published, as they allow the shared use of the energy generated, thus reducing the costs of PV installations.

CRediT authorship contribution statement

Daniel Dasí-Crespo: Conceptualization, Methodology, Software, Writing – original draft, Visualization, Writing – review & editing. **Carlos Roldán-Blay:** Methodology, Software, Investigation, Formal analysis, Validation, Writing – review & editing. **Guillermo Escrivá-Escrivá:** Conceptualization, Methodology, Data curation, Visualization, Supervision, Writing – review & editing. **Carlos Roldán-Porta:** Conceptualization, Investigation, Resources, Project administration, Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

Table A1. 1
Urban planning details of the plots and technical details of the self-consumption PV installations.

Plot	Use	Graphic area (m^2)	Electric demand (kW)	Contracted power (kW)	Contracted Tariff	Number of panels	Peak power (kWp)	Useful power (kW)	Installation cost (€)
1	Residential	58	4.23	4.60	Tariff 2.0A	–	–	–	–
2	Industrial	77	3.42	3.45	Tariff 2.0.DHA	–	–	–	–
3	Industrial	122	4.19	4.60	Tariff 2.0A	–	–	–	–
4	Residential	258	4.28	4.60	Tariff 2.0A	7	2.31	1.47	3903.90
5	Residential	131	4.55	4.60	Tariff 2.0A	7	2.31	1.47	3903.90
6	Warehouse	112	4.65	4.60	Tariff 2.0A	9	2.97	1.90	5019.30
7	Residential	89	4.65	4.60	Tariff 2.0A	6	1.98	1.26	3346.20
8	Residential	44	3.24	3.45	Tariff 2.0A	6	1.98	1.36	3346.20
9	Residential	42	4.37	4.60	Tariff 2.0A	6	1.98	1.36	3346.20
10	Residential	74	4.55	4.60	Tariff 2.0A	3	0.99	0.68	2500.00
11	Residential	154	4.09	4.60	Tariff 2.0.DHS	–	–	–	–
12	Residential	186	4.42	4.60	Tariff 2.0A	7	2.31	1.36	3903.90
13	Residential	34	3.14	3.45	Tariff 2.0A	–	–	–	–
14	Residential	54	3.48	3.45	Tariff 2.0A	–	–	–	–
15	Residential	62	4.65	4.60	Tariff 2.0A	–	–	–	–
16	Residential	34	3.24	3.45	Tariff 2.0A	–	–	–	–
17	Residential	42	3.21	3.45	Tariff 2.0A	–	–	–	–
18	Residential	239	4.51	4.60	Tariff 2.0.DHA	10	3.30	2.11	5577.00
19	Residential	116	4.28	4.60	Tariff 2.0A	5	1.65	1.05	2788.50
20	Industrial	180	4.60	4.60	Tariff 2.0A	10	3.30	2.11	5577.00
21	Residential	223	4.23	4.60	Tariff 2.0.DHS	10	3.30	2.11	5577.00
22	Unbuilt	196	0.00	0.00	Tariff 2.0A	–	–	–	–
23	Warehouse	179	3.42	3.45	Tariff 2.0.DHS	–	–	–	–
24	Residential	91	3.38	3.45	Tariff 2.0.DHA	6	1.98	1.26	3346.20
25	Residential	426	6.62	6.90	Tariff 2.0.DHA	16	5.28	3.65	8923.20
26	Residential	58	4.65	4.60	Tariff 2.0.DHS	6	1.98	1.36	3346.20
27	Residential	118	4.55	4.60	Tariff 2.0A	10	3.30	2.26	5577.00
28	Residential	33	3.38	3.45	Tariff 2.0A	–	–	–	–
29	Residential	108	4.60	4.60	Tariff 2.0A	7	2.31	1.36	3903.90
30	Residential	78	4.42	4.60	Tariff 2.0A	10	3.30	1.94	5577.00
31	Residential	109	4.65	4.60	Tariff 2.0A	6	1.98	1.16	3346.20
32	Warehouse	105	3.28	3.45	Tariff 2.0A	–	–	–	–
33	Residential	409	5.29	5.75	Tariff 2.0.DHA	15	4.95	2.91	8365.50
34	Residential	54	3.45	3.45	Tariff 2.0.DHS	2	0.66	0.39	2500.00
35	Residential	31	3.24	3.45	Tariff 2.0A	5	1.65	0.97	2788.50
36	Residential	150	4.32	4.60	Tariff 2.0.DHA	–	–	–	–
37	Residential	119	4.60	4.60	Tariff 2.0A	6	1.98	1.16	3346.20
38	Residential	96	4.37	4.60	Tariff 2.0A	5	1.65	0.97	2788.50
39	Residential	98	4.23	4.60	Tariff 2.0.DHS	6	1.98	1.16	3346.20
40	Residential	76	4.60	4.60	Tariff 2.0A	6	1.98	1.16	3346.20
41	Residential	124	4.51	4.60	Tariff 2.0A	7	2.31	1.36	3903.90

(*continued on next page*)

Table A1. 1 (*continued*)

Plot	Use	Graphic area (m^2)	Electric demand (kW)	Contracted power (kW)	Contracted Tariff	Number of panels	Peak power (kWp)	Useful power (kW)	Installation cost (€)
42	Residential	139	4.14	4.60	Tariff 2.0A	6	1.98	1.36	3346.20
43	Residential	67	4.55	4.60	Tariff 2.0A	6	1.98	1.16	3346.20
44	Warehouse	60	4.46	4.60	Tariff 2.0.DHA	–	–	–	–
45	Residential	80	4.37	4.60	Tariff 2.0A	6	1.98	1.36	3346.20
46	Residential	75	4.32	4.60	Tariff 2.0A	10	3.30	2.26	5577.00
47	Residential	89	4.42	4.60	Tariff 2.0A	4	1.32	0.90	2500.00
48	Residential	122	4.51	4.60	Tariff 2.0A	10	3.30	2.26	5577.00
49	Residential	180	4.60	4.60	Tariff 2.0A	10	3.30	2.26	5577.00
50	Residential	48	4.14	4.60	Tariff 2.0A	4	1.32	0.90	2500.00
51	Residential	52	3.21	3.45	Tariff 2.0A	8	2.64	1.81	4461.60
52	Residential	80	4.19	4.60	Tariff 2.0A	–	–	–	–
53	Residential	127	4.65	4.60	Tariff 2.0A	6	1.98	1.16	3346.20
54	Residential	64	4.28	4.60	Tariff 2.0.DHS	4	1.32	0.78	2500.00
55	Industrial	114	4.19	4.60	Tariff 2.0A	–	–	–	–
56	Residential	121	4.65	4.60	Tariff 2.0.DHA	9	2.97	2.15	5019.30
57	Warehouse	144	4.23	4.60	Tariff 2.0.DHA	–	–	–	–
58	Residential	84	4.65	4.60	Tariff 2.0A	8	2.64	1.92	4461.60
59	Residential	96	3.11	3.45	Tariff 2.0A	–	–	–	–
60	Industrial	100	3.07	3.45	Tariff 2.0A	–	–	–	–
61	Industrial	90	4.09	4.60	Tariff 2.0A	–	–	–	–
62	Industrial	109	3.17	3.45	Tariff 2.0.DHA	–	–	–	–
63	Residential	75	4.65	4.60	Tariff 2.0A	5	1.65	1.25	2788.50
64	Residential	91	4.46	4.60	Tariff 2.0.DHA	5	1.65	0.97	2788.50
65	Residential	87	4.19	4.60	Tariff 2.0A	10	3.30	1.94	5577.00
66	Warehouse	144	4.09	4.60	Tariff 2.0.DHS	–	–	–	–
67	Residential	213	4.19	4.60	Tariff 2.0.DHA	10	3.30	2.39	5577.00
68	Industrial	130	4.60	4.60	Tariff 2.0A	–	–	–	–
69	Unbuilt	121	0.00	0.00	Tariff 2.0A	–	–	–	–
TOTAL		**7891**	**280.69**			**336**	**105.60**	**68.13**	**181,483.10**

Table A1. 2
Urban planning details of the plots and technical details of the self-consumption PV installations.

Plot	Annual consumption cost (€)				Payback (years)		
	Without PV (S_0)	PV without sale (S_1)	PV Net billing (S_2)	PV Direct sell (S_3)	PV without sale (S_1)	PV Net billing (S_2)	PV Direct sell (S_3)
1	–	–	–	–	–	–	–
2	–	–	–	–	–	–	–
3	–	–	–	–	–	–	–
4	798.96	664.27	621.89	555.40	28.98	22.05	16.03
5	784.27	634.66	595.01	533.66	26.09	20.63	15.58
6	781.83	609.59	554.78	468.30	29.14	22.11	16.01
7	957.45	802.59	774.09	730.64	21.61	18.25	14.75
8	470.37	369.90	325.98	256.02	33.30	23.17	15.61
9	644.89	514.72	476.74	417.21	25.71	19.90	14.70
10	771.27	677.47	664.30	644.27	26.65	23.37	19.69
11	–	–	–	–	–	–	–
12	641.37	503.01	466.68	410.00	28.21	22.35	16.87
13	–	–	–	–	–	–	–
14	–	–	–	–	–	–	–
15	–	–	–	–	–	–	–
16	–	–	–	–	–	–	–
17	–	–	–	–	–	–	–
18	746.88	583.68	517.25	411.72	34.17	24.29	16.64
19	757.75	635.50	610.55	572.08	22.81	18.94	15.02
20	893.78	693.58	633.94	540.89	27.86	21.46	15.80
21	631.50	472.78	405.56	298.75	35.14	24.68	16.76
22	–	–	–	–	–	–	–
23	–	–	–	–	–	–	–
24	512.99	401.89	364.83	306.67	30.12	22.59	16.22
25	1116.79	855.56	736.12	546.24	34.16	23.44	15.64
26	911.49	762.89	728.89	676.22	22.52	18.33	14.22
27	797.46	635.97	561.83	443.56	34.53	23.67	15.76
28	–	–	–	–	–	–	–
29	681.54	554.17	515.52	454.99	30.65	23.51	17.23
30	743.57	589.07	528.40	432.45	36.10	25.92	17.93
31	838.98	705.13	676.98	633.95	25.00	20.66	16.32
32	–	–	–	–	–	–	–
33	885.45	643.83	555.27	415.78	34.62	25.34	17.81
34	649.64	587.69	581.89	573.31	40.35	36.90	32.75
35	570.96	460.75	436.91	400.38	25.30	20.80	16.35
36	–	–	–	–	–	–	–

(*continued on next page*)

Table A1. 2 (*continued*)

Plot	Annual consumption cost (€)				Payback (years)		
	Without PV (S_0)	PV without sale (S_1)	PV Net billing (S_2)	PV Direct sell (S_3)	PV without sale (S_1)	PV Net billing (S_2)	PV Direct sell (S_3)
37	878.08	739.31	712.09	670.71	24.11	20.16	16.14
38	717.06	594.90	573.36	540.84	22.83	19.41	15.82
39	791.81	664.29	635.47	590.77	26.24	21.40	16.64
40	873.72	738.51	710.51	667.90	24.75	20.50	16.26
41	790.25	644.59	609.58	555.39	26.80	21.61	16.62
42	585.46	466.47	426.19	362.73	28.12	21.01	15.02
43	667.63	533.24	505.11	462.25	24.90	20.59	16.29
44	–	–	–	–	–	–	–
45	703.95	549.15	516.06	465.05	21.62	17.81	14.01
46	787.91	587.66	521.09	416.50	27.85	20.90	15.02
47	860.48	741.62	722.97	694.73	21.03	18.18	15.08
48	839.20	653.96	584.09	474.04	30.11	21.86	15.27
49	901.56	702.22	635.45	530.51	27.98	20.96	15.03
50	844.65	722.14	704.12	677.06	20.41	17.79	14.92
51	506.44	380.07	320.68	225.02	35.30	24.02	15.85
52	–	–	–	–	–	–	–
53	873.72	743.59	714.75	670.47	25.71	21.05	16.46
54	711.42	611.36	594.78	569.82	24.98	21.43	17.65
55	–	–	–	–	–	–	–
56	759.10	570.82	507.28	407.66	26.66	19.93	14.28
57	–	–	–	–	–	–	–
58	710.02	541.02	484.65	395.52	26.40	19.80	14.19
59	–	–	–	–	–	–	–
60	–	–	–	–	–	–	–
61	–	–	–	–	–	–	–
62	–	–	–	–	–	–	–
63	800.79	663.12	631.79	583.31	20.26	16.50	12.82
64	715.96	593.48	572.42	540.31	22.77	19.43	15.88
65	643.59	501.20	438.40	338.27	39.17	27.18	18.27
66	–	–	–	–	–	–	–
67	673.65	490.93	415.03	294.91	30.52	21.56	14.73
68	–	–	–	–	–	–	–
69	–	–	–	–	–	–	–
TOTAL					**27.99**	**21.71**	**16.27**

Appendix 2

Table A2. 1
PV generation plant associated costs on a rural site.

Item	Total cost (€) VAT included	Total cost (€/Wp) VAT included
Plot	19,247.60	0.02546
Geotechnical study	3600.00	0.00476
Engineering cost (project drafting)	14,084.03	0.01863
Engineering cost (site management)	9389.35	0.01242
Industry legalisation	1032.83	0.00137
Registration as electricity generator	1294.85	0.00171
School approval costs	1722.44	0.00228
Other authorisations (environmental, public utility, installer …)	1032.83	0.00137
PV GP	757,579.20	1.00209
Evacuation power line	42,862.18	0.05670
Transformer Substation	67,040.78	0.08868
Commissioning	2600.00	0.00344
TOTAL	**921,486.09**	**1.22**

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