Energy Strategy Reviews 45 (2023) 101055

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

Sharing approaches in collective self-consumption systems: A techno-economic analysis of the Spanish regulatory framework

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ARTICLE INFO

Handling Editor: Mark Howells

Keywords:
Electricity markets
Self-consumption
Prosumer
Renewable energy communities

ABSTRACT

This paper proposes an analysis of the current regulatory framework for collective self-consumption in Spain. This regulatory framework proposes a model based on constant distribution coefficients for the allocation of self-consumed energy, as well as a constant distribution for the allocation of economic rights corresponding to surplus energy. The main advantage of this model is its simplicity and ease of implementation. Nonetheless, it has the disadvantage that part of the energy produced cannot be used (in economic terms) by the participants in the shared self-consumption system, which limits the economic potential of these facilities and therefore makes them less attractive to new investors. Therefore, this work proposes a techno-economic analysis of the influence of the current regulatory framework for collective self-consumption on the profitability of this type of projects. The analysis shows that, regardless of its simplicity of implementation, the existing scheme is not fully efficient, as part of the self-generated energy is not allocated to the community's consumption or surplus. This means that investors in the project obtain a profitability lower than the real potential of the installation. Furthermore, following the analysis carried out, an alternative distribution scheme is proposed that considerably improves the profitability of this type of projects.

1. Introduction

We are currently at a historic crossroads where the energy model on which we have relied since the beginning of the industrial revolution is in inexorable decline. The decline of oil and the saturation of CO2 sinks are becoming increasingly evident. In addition, the high levels of energy dependence in certain countries, such as Spain, the uncertainty of supply and oil and gas price volatility resulting from geopolitical tensions. Furthermore, there is an increasingly large group of people who are concerned about environmental sustainability and opposed to the use of certain technologies that cause greenhouse gas emissions, which results in a stronger focus by regulatory authorities on the promotion of new energy policies on renewable energies. All of this, in addition to the development of significant scientific advances, represents an opportunity in which the European Union (EU) intends to take the lead in promoting renewable energy sources, reducing emissions and saving energy consumption in the EU through the Clean Energy for all Europeans package [1] with the aim of fulfilling the commitments acquired in the framework of the Paris Agreement. These objectives have recently been reinforced with the so-called Green Deal, with a view to achieving a carbon-neutral economy in Europe by 2050, as well as by the Next Generation EU recovery plan, in which climate action is one of the fundamental pillars.

Following this roadmap, it is clear that the energy system will have to undergo considerable evolution and deep decarbonisation in order to achieve the proposed sustainability objectives. The development of large-scale storage, the increasing electrification of transport and the implementation of smart grids together with distributed generation will be the answers to overcome the present and imminent energy challenges. With the approval of the European Renewable Energy Directive (RED) in 2018 [2], the aim is to provide the necessary regulatory impetus to enable the Member States of the European Union to achieve new forms of sustainability that until now have been subject to the choice of each national regulation. One of these lines of action corresponds to the implementation of collective self-consumption, as it lays the foundations for the development of energy communities.

The RED provides the basic definitions and requirements for

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https://doi.org/10.1016/j.esr.2023.101055
Received 19 July 2022; Received in revised form 22 December 2022; Accepted 3 January 2023
Available online 8 January 2023

Abbreviations

Collective self-consumption Renewable generation installation whose resource is shared between the different participants
i Index referring to the i-th consumer
h Index referring to the h-th hour
m Index referring to the m-th month
t Index referring to the t-th year
n Number of consumers of the collective self-consumption community
$E_{PV\ h}$ - Hourly energy generated
Energy generated by the photovoltaic installation in a given hour
$E_{L\ h,i}$ Individual hourly energy consumed
hourly energy load demanded by the i-th consumer
$E_{SC\ h,i}$ Individualised self-consumed hourly energy Share of hourly energy produced by the self-generation system assigned to the i-th customer
$E_{G\ h,i}$ Individual hourly energy consumed from the grid
Hourly energy received exclusively from the grid by the i-th customer
$E_{S\ h,i}$ Individualised surplus hourly energy
Surplus energy (fed into the grid) from the self-generation system assigned to the i-th customer
$CP_{h,i}$ Individualised hourly consumption profile of the i-th consumer
β_i Coefficient of distribution of the energy generated among the consumers participating in collective self-consumption
α_i Coefficient of distribution of surplus energy among consumers participating in collective self-consumption
$T_{amb\ h}$ Hourly ambient air temperature
$G_{amb\ h}$ Hourly global irradiance on a fixed plane
$P_{m\ h}$ Hourly spot market prices
$C_{b\ h}$ Hourly balancing costs
$PVPC_h$ Hourly price of the regulated tariff for domestic customers
$C_{V\ i,m}$ Variable costs of the energy bill for the i-th consumer during the month m. It corresponds to the compensable part of the invoice.
$C_{F\ i,m}$ Fixed costs of the energy bill for the i-th consumer during the month m. It corresponds to the non-clearable part of the invoice.
$P_{C\ i}$ Contracted power by the i-th consumer
$P_{r\ i}$ Rated power of the electricity installation of the i-th consumer
P_{PV} Rated power of PV generation system
$P_{T\ m}$ Power term
$C_{T\ i,m}$ Total costs of the energy bill for the i-th consumer during the month m
I_{inv} Capital expenditure for undertaking the investment associated with the self-consumption installation
LS Life span of the installation
$OpEx_t$ Expenditure on operation and maintenance of the facility in year t of its lifetime.
NPV Net present value
IRR Internal Rate of Return
CF_t Cash flow for year t
EU European Union
IRR Internal rate of return
RED Renewable Energy Directive

collective self-consumption activities and energy communities and each member state takes them as a pillar of its national regulations. However, national regulations may differ significantly in several aspects, ranging from type of participants and stakeholders, administrative procedures, technical requirements such as physical extension, maximum size of the renewable generation system, criteria for energy distribution among consumers or even in economic matters on the incentives offered, [3].

Table 1 shows an overview of the main features of the regulatory framework concerning collective self-consumption in a selection of countries neighbouring Spain. With regard to energy sharing, Spain and Portugal adopt a very similar approach based on sharing coefficients. The same approach is also used in France, although prosumers can also choose to sell energy locally. In Germany there is currently no concept of shared self-consumption, although it is possible for an energy trading company to operate a PV system and sell the energy within the community. In Italy, all prosumers buy energy from the grid and receive compensation for the energy sold by the PV system on the basis of actual metering. It is also worth noting that in Spain, Portugal, France and Italy it is possible to set up a shared self-consumption community in neighbouring residences using the distribution grid, whereas the German regulation does not yet consider this possibility. Likewise, there are also notable differences in terms of the maximum power of the PV installation, being 100 kW in Spain and Germany, 200 kW in Italy, 3 MW in France, while in Portugal there is no limit (although as the power increases the administrative requirements are increasingly restrictive).

Table 1
Technical features of each consumer considered in the case study. Compiled from Refs. [4–6].

Country	Surplus payment scheme	Proximity through the distribution network	Maximum rated power restrictions
Spain	Sharing coefficients	Yes	100 kW
France	Sharing coefficients and local selling	Yes	3 MW
Germany	Third-party supplier management	No	100 kW
Portugal	Sharing coefficients	Yes	No power limit
Italy	Virtual sharing	Yes	200 kW

This disparity is indicative of the lack of maturity of the regulatory frameworks to achieve the full deployment of collective self-consumption and renewable communities, because while it is true that many guidelines must be according to the perspective of each country, certain aspects should have a common denominator. Specifically, this paper focuses on the analysis of the distribution of self-consumed energy under the regulatory framework of collective self-consumption in Spain and how an appropriate policy can lead to a significant improvement in the rate of profitability associated with the deployment of collective self-consumption.

There are several studies in the scientific literature that analyse the potential of collective self-consumption, both from a purely technical and regulatory point of view.

In [7] a bi-objective model was defined for the maximisation of the energy resources coming from a self-consumption installation for a group of houses, both in an individual and shared modality. Specifically, the management of a collaborative microgrid was studied, which should consider both the allocation of resources and the scheduling of tasks in a limited time horizon using mixed-integer linear programming. The authors deduced that it was possible to meet the users' needs with a photovoltaic (PV) plant and energy storage of lower capacity, and therefore lower installation and maintenance costs. The same conclusions were described by Ref. [8], where a community of neighbours is subjected to a gradual electrification process, understanding the group of dwellings as a single unit to achieve the maximum use of resources [9]. introduces two smart energy management models for the Spanish electricity system in terms of power consumption savings, including in the models aspects such as energy savings measures, smart meters, self-supply and electric vehicles. In Ref. [10] a residential PV system located in different locations in Spain and France is analysed from an economic and environmental point of view.

Regarding purely regulatory analyses, in Ref. [3] a review and comparison of the regulatory frameworks in force in the EU Member States pertaining to self-consumption was carried out, which suggested the importance of defining tariffs according to the role adopted by the energy communities in the electricity system, taking into account the appropriate distribution of system costs among consumers as well as the presence of certain organisational aspects to facilitate the extension of collective self-consumption in EU countries. In reference to the analysis of the regulatory framework in Spain, in Ref. [11] the economic viability impact of a system on an individual self-consumption system was examined by incorporating the constraints established by the previous regulatory framework for self-consumption in Spain [12], implemented in 2015 and in force until 2018. The model established the optimal scheduling for one day and did not consider the optimal sizing of the installation. As a result, the role of relevant energy policies in achieving an efficient optimality criterion was found to be of great importance. It should also be noted that the study is based on a now phased out regulation that did not recognise the right to collective self-consumption [13]. also carried out a study of the profitability of individual self-consumption in Spain, considering the former regulatory framework established by Ref. [12], focusing on the influence of the number of inhabitants in the residence, and its comparison with the profitability that would be obtained under the regulatory framework of other European countries.

One of the first studies on the profitability of residential PV self-consumption under the respective regulations currently in force in Spain since 2019 [14] was carried out in Ref. [15]. Taking the case of a single average home as the object, it was proven that for an installation of optimum size, the economic profitability obtained would represent an effective saving compared to conventional electricity billing. Nevertheless, it should be noted that both studies do not analyse the implications of the new regulatory framework in Spain in the field of collective self-consumption. In the same line of work [16], analysed the profitability of domestic and industrial consumers using individual self-consumption, taking into account the regulations currently in force. Likewise [17], determined the importance of sizing the installation according to techno-economic optimisation and the consumption needs of households, also considering the geographical location. As a result, and making use of the current regulations on self-consumption in Spain [14], it was indicated the need to take into account from a regulatory point of view the existing differences between the different climatic regions in order to harmonise the profitability of self-consumption throughout the national territory.

In addition to the aforementioned works, it is also worth noting that there are several studies on the implementation of blockchain and peer-to-peer technology applied to the development of local energy markets [18]. Nonetheless, there are still no regulatory frameworks in place to enable the implementation of these models. Therefore, the subject matter of these works, although of great importance for the future development of energy regulation, has a mainly long-term perspective, which contrasts with the focus of this paper, which aims to analyse current regulatory developments.

The literature review shows a lack of studies that analyse the efficiency of the regulatory frameworks on collective self-consumption currently in place. This is mainly due to the fact that the regulation of collective self-consumption at a global level is currently (mid-2022) really scarce, being Spain one of the first countries to implement this modality of collective self-consumption, a previous step for the future development of energy communities and local markets. In this sense, this paper contributes to the state of the art by analysing the current scheme in Spain from a techno-economic point of view.

To this end, a collective self-consumption installation has been modelled from a technical and economic point of view. In this way, through the implementation of several case studies, we have highlighted the situations in which the current remuneration scheme in Spain is not fully efficient from the point of view of the profitability potential of the installation, as on certain occasions it does not allow for an optimal distribution of the energy produced by the installation in the community as a whole.

Likewise, as a result of the analysis carried out in this work, an alternative remuneration scheme is also proposed that allows for a better use in economic terms of the energy self-produced by the community. This alternative scheme is based on a proportional distribution of the energy produced according to actual energy consumption, which is also simple to implement from both a technical and regulatory point of view.

Therefore, the results obtained in this work may be of interest to other researchers involved in the analysis of the regulatory framework and techno-economic behaviour of self-consumption communities. Likewise, the conclusions obtained may also be of interest to the regulatory authorities through to the policy implications raised, as well as to the participants of the self-consumption communities themselves (including end consumers and energy service companies), allowing a better understanding of the overall behaviour of the installation.

After this brief introduction, the rest of the paper is organised as follows: Section 2 presents an overview of the current regulatory framework for collective self-consumption in Spain, Section 3 describes the model implemented to perform the techno-economic analysis of the regulatory framework, Section 4 shows the results obtained in the proposed case studies, and finally Section 5 provides the conclusions and policy implications drawn from this work.

2. Overview of the regulatory framework for collective self-consumption in Spain

The right for an individual consumer to generate part of their energy needs locally has been included in Spanish regulation since 2013 [19] that established the technical and economic conditions for self-consumption introduced a set of regulatory barriers, including the complexity of the administrative process and the establishment of a back-up toll (usually known as a solar tax) to be paid for self-consumed energy. These barriers were eliminated by Royal Decree-Law 15/2018 [20], which also introduced the right to collective self-consumption, a regulation that was complemented by the subsequent regulatory development established in Royal Decree 244/2019 [14], whose main characteristics with regard to collective self-consumption are described in the following lines.

The main feature of interest, from a techno-economic point of view, is the criterion for the distribution of the energy produced by the PV panels in a given hour h, $E_{PV\,h}$. For this purpose, the regulation proposes a proportional allocation according to the distribution coefficients, β_i. These coefficients (constant for all the hours of a billing period, namely, one month) can be established by agreement of the participants of the self-consumption community or, alternatively, they are established by default by the regulations, according to the following expression:

$$\beta_i = \frac{P_{Ci}}{\sum_{i=1}^{n} P_{Ci}} \quad (1)$$

where P_{Ci} is the contracted power by the i-th consumer, assuming one single contracted power for each customer.

In this way, the individualised self-consumed hourly energy for the i-th consumer, $E_{SC\,h,i}$, (i.e., the energy from the PV system that from an economic point of view is attributed to a given individual consumer) is obtained by means of:

$$E_{SC\ h,i} = \begin{cases} \beta_i \cdot E_{PV\ h} & \text{if} \quad \beta_i \cdot E_{PV\ h} < E_{L\ h,i} \\ E_{L\ h,i} & \text{if} \quad \beta_i \cdot E_{PV\ h} \geq E_{L\ h,i} \end{cases} \tag{2}$$

where $E_{L\ h,i}$ is the total energy demanded by the i-th consumer during hour h.

The hourly energy requirement from the grid to be received by each customer, $E_{G\ h,i}$, is:

$$E_{G\ h,i} = E_{L\ h,i} - E_{SC\ h,i} \tag{3}$$

Similarly, the current regulation also contemplates by default a criterion for the distribution of surplus energy based on fixed coefficients of depending on the rated power of each customer $P_{r\ i}$ and the rated power of the PV panels, P_{PV}:

$$\alpha_i = \frac{P_{r\ i}/P_{PV}}{\sum_{i=1}^{n} P_{r\ i}/P_{PV}} \tag{4}$$

Nevertheless, it should be noted that, as with the distribution coefficients for the allocation of individualised self-consumed energy, the regulation provides that these coefficients can be agreed by the members of the energy community (although in any case constant over time).

In this way the individualised energy surplus assigned to each customer, $E_{S\ h,i}$ for a given hour h, would be obtained by means of:

$$E_{S\ h,i} = \alpha_i \left(E_{PV\,h} - \sum_{i=1}^{n} E_{SC\,h,i} \right) \tag{5}$$

It is worth mentioning that the main advantage of this scheme is its simplicity, as it only requires 1 m for the PV system plus the meters of each customer, allowing the distribution of energy (both self-consumed and surplus) *a posteriori* without the need to exchange information between the meters of each individual customer, which considerably facilitates the management of the information, as each customer can belong to different suppliers. However, as will be shown below, this distribution system is not optimal because, depending on the consumption profiles of the customers, part of the energy produced by the photovoltaic panels may not be allocated to all consumers either as self-consumed energy or as surplus energy.

3. Techno-economic model of the collective self-consumption system

This section describes the models used to simulate the techno-economic behaviour of an energy community based on a collective self-consumption system, subject to the regulatory framework currently in force in Spain (described in the previous section). To this end, the materials and methods used to model the photovoltaic energy production, the equations that define the cost of energy for domestic consumers, as well as the sale price of surplus energy and, finally, the formulation to assess the economic behaviour of the installation will be described. Fig. 1 shows schematically the methodology proposed in this work. The calculation module is fed mainly with two sets of data: (i) the data related to the calculation of the energy produced by the PV panels and (ii) the data necessary for the calculation of the energy billing. These data are then processed to obtain the distribution coefficients of the self-consumed energy and the energy surplus. As detailed in Section 4 below, four different approaches will be considered for the calculation of the sharing coefficients (depending on the assumptions considered about the regulatory framework). Finally, once the distribution coefficients have been obtained, indicators are calculated to evaluate the economic performance of each of the approaches analysed.

3.1. Energy produced by the PV panels

The energy generated by the PV system for each hour of the year, $E_{PV\ h}$, can be obtained as [21]:

$$E_{PV\,h} = (1 - PV_{losses}) \cdot (P_{G_{inst}} \cdot (G_{amb\ h} / 1000) \cdot (1 - \gamma \cdot (T_h - 25))) \tag{6}$$

where PV_{losses} are the typical losses in PV systems (such as dirt and commutation losses), P_{Ginst} is the rated power of the PV system, γ is the temperature coefficient of the modules, $G_{amb\ h}$ is the hourly irradiance on a fixed plane and T_h is the temperature of the cells obtained as follows:

$$T_h = T_{amb\,h} + (G_{amb\,h} / 800) \cdot (T_{NOC} - 20) \tag{7}$$

where $T_{amb\ h}$ is the hourly ambient air temperature, while T_{NOC} is the nominal operating temperature of the cells.

3.2. Energy prices

The economic behaviour of the self-consumption installation is conditioned by the electricity tariffs of the consumers. For this reason, this study considers that for the purchase of energy, domestic consumers are covered by the regulated tariff PVPC (Voluntary Price for Small Consumers). Thus, the hourly energy purchase price, $PVPC_h$, has been determined taking into account the tariff structure and components (i.e., considering charges, tolls, taxes and energy costs) in force in Spain IDAE, «IDAE, 2021. Informe de precios energéticos regulados.». As for the energy acquisition costs, the average hourly spot market prices, $P_{m\ h}$, during the years 2014–2019 obtained from the market operator OMIE have been considered. On the other hand, the surplus energy produced by the photovoltaic panels is remunerated according to current regulations at the daily market price minus balancing costs, $C_{b\ h}$. Thus, the variable costs of the energy bill, $C_{V\ i,m}$, for the i-th consumer during month m, can be determined by the following expression:

$$C_{V\ i,m} = \sum_{h=1} E_{G\ h,i} \cdot PVPC_h - \sum_{h=1} E_{S\ h,i} \cdot (P_{m\ h} - C_{b\ h}), C_{V\ i,m} \geq 0 \forall i \tag{8}$$

Please note that according to current regulations in Spain, revenues from energy surpluses cannot exceed the cost of acquiring the energy over a billing period (i.e., one month). In this way, the regulatory framework prevents bills from being negative and the self-consumption system from being oversized in order to obtain extra revenues from the

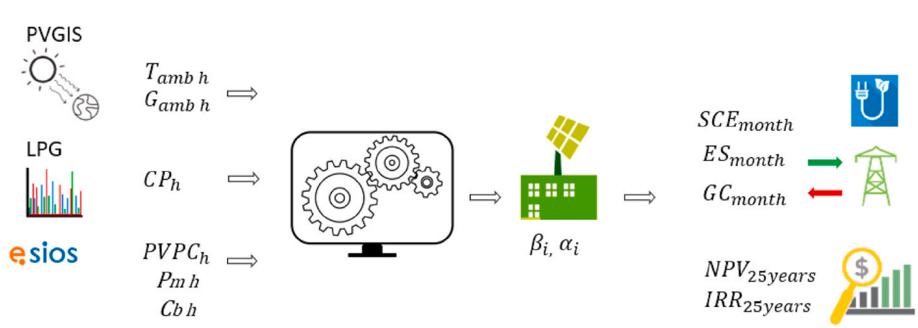

Fig. 1. Techno-economic model implementation.

sale of surplus energy.

In the calculation of the monthly energy bill it is also necessary to take into account the fixed costs, $C_{F\ i,m}$, which are determined as the product of the contracted power by the power term, $P_{T\ m}$:

$$C_{F\ i,m} = P_{C\ i} \cdot P_{T\ m} \tag{9}$$

Finally, the total cost, $C_{T\ i,m}$, of the energy bill of each consumer is obtained as the sum of the fixed costs plus the variable costs:

$$C_{T\ i,m} = C_{V\ i,m} + C_{F\ i,m} \tag{10}$$

3.3. Economic evaluation

In order to carry out the economic evaluation, it is proposed to analyse the incremental net present value of the investment in the shared self-consumption system with respect to the original situation in which all consumers are conventional. In other words, the economic evaluation is based on considering as benefits the savings obtained in the electricity bill after the installation of the self-consumption system. In this way, the annual cash flows for the t-th year, CF_t, can be determined as follows:

$$CF_t = \sum_{i=1}^{n} \sum_{m=1}^{12} \left(C_{T\ i,m}^{Conventional} - C_{T\ i,m}^{Selfconsumption} \right) - OpEx_t \tag{11}$$

where $OpEx_t$ corresponds to the operation and maintenance costs of the PV installation during the year t-th year.

Thus, the net present value will be determined by means of:

$$NPV = -I_{inv} + \sum_{t=1}^{LS} \frac{CF_t}{(1+k)^t} \tag{12}$$

Where I_{inv} is the initial investment required in the self-consumption system, LS is the life span of the project, k is the discount rate.

It is also worth mentioning that another indicator commonly used in the economic evaluation of projects is the internal rate of return (IRR), which corresponds to the discount rate that makes the NPV zero, according to equation (13):

$$0 = -I_{inv} + \sum_{t=1}^{LS} \frac{CF_t}{(1+IRR)^t} \tag{13}$$

4. Case study

In order to address the analysis of the regulatory framework in Spain on energy management regarding collective self-consumption, a case study is proposed corresponding to a set of 20 dwellings with different consumption profiles. Table 2 shows the contracted power of each dwelling, as well as its associated installed power.

The hourly consumption profiles of each house have been determined over a full year using the LoadProfileGenerator program [22]. The energy production by the PV system has been obtained using the model introduced in Section 3, assuming a housing community located in Seville (37°21′57 "N 5°58′59 "W) and taking into consideration the irradiance provided by PVGIS [23]. Regarding electricity prices, a base scenario has been considered corresponding to the average hourly prices during the period 2015–2019 for the 25 years of the lifetime of the installation. In the case of energy purchase prices, as mentioned in Section 3, the regulated PVPC tariff [24] has been considered, and the spot market prices [25] have been used for the sale of surplus energy (please note that the self-consumption surplus compensation prices came into force in April 2019. However, these prices are very similar to those of the spot market). The time series corresponding to the aforementioned hourly data (energy demand per household, hourly energy produced by the PV panels, energy price for the domestic consumer and selling price of the surplus) are provided at Mendeley Data [26]. The

Table 2
Technical features of each consumer considered in the case study.

	Customer																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Contracted Power (kW)	5.0	6.0	3.8	7.0	6.2	3.3	5.6	2.5	6.0	4.6	3.7	3.0	2.6	6.0	7.0	3.2	4.9	3.7	4.6	3.6
Installed Power (kW)	5.75	9.2	5.75	9.2	9.2	5.75	5.75	5.75	9.2	5.75	5.75	5.75	5.75	9.2	9.2	5.75	5.75	5.75	5.75	5.75

analysis has been carried out by gradually increasing the installed PV generation power from 10 kW to 50 kW in 5 kW intervals (please note that the maximum of 50 kW is imposed by the maximum available roof area of the residential building considered in this paper).

The remaining techno-economic data used in the analysis are shown in Table 3.

4.1. Analysed approaches

This paper proposes the analysis and comparison of four different approaches in order to examine the current regulatory framework for the allocation scheme of self-consumed and surplus energy.

- **Ideal energy distribution (IED)**: this approach addresses an ideal situation in which the use of energy from generation is complete, i.e., all the energy available during production hours will be used as a priority to supply the needs of all the dwellings as a whole, without any distinction of interests. Consequently, the energy remaining at hours when generation exceeds demand will be used for the sale of surpluses. In practical terms, this approach corresponds to the assumption that the whole community is considered as a single individual self-consumer.
- **Static energy distribution – Regulatory established (SED-RE)**: this approach corresponds to the direct application of the regulatory framework for collective self-consumption in Spain. In this alternative, two aspects stand out. Firstly, the allocation of the distribution coefficients remains unchanged. Secondly, the allocation of self-produced energy is determined according to a proportionality criterion linked to the contracted and installed power of each consumer. On the one hand, self-consumed energy is allocated taking into account the contracted power of each customer as set out in equations (1) and (2), while the distribution of surplus energy is determined on the basis of the installed power of each of the participants over the total surplus energy remaining, as set out in equations (4) and (5).
- **Static energy distribution - neighbours' agreement (SED-NA)**: this case corresponds to a variant of the previous one. As mentioned in Section 2, the current regulation in Spain also contemplates that the distribution coefficients can be established by agreement by the neighbours, although in any case constant for all hours and billing period (i.e. each month). The coefficients considered (both for the allocation of individualised self-consumed energy and individualised surplus energy) in this case are obtained by means of an optimisation algorithm based on the default multi-start algorithm of Matlab, considering the maximisation of the NPV as the objective. This approach corresponds to the best possible theoretical situation under the current regulatory framework, since the optimised solution considers perfect information in the consumption, generation and price profiles (i.e. these variables are considered to be known in advance for the calculation of the sharing coefficients).
- **Proportional energy distribution (PED)**: an alternative approach to the previous ones is proposed based on an *ex post* distribution, i.e. a distribution based on actual hourly meter readings. In this way, for each hour, the individualised self-consumed energy is allocated in proportion to the energy consumed by each customer. The surplus distribution coefficients are the same as those for the distribution of self-consumed energy, i.e., proportional to hourly consumption.

Table 3
Main techno-economic data considered in the test cases.

PV system lifetime (r)	25 years
Discount rate (k)	4%
PV system initial investment (CAPEX)	908.92 €/kW
Annual operating and maintenance cost (OPEX)	15 €/kW/year
Annual degradation factor of the PV system	0.5%

As Table 4 shows, the differences between the four approaches analysed are significant, with profitability improving as the flexibility of the regulatory framework on the distribution of self-produced energy increases. In this way, it can be seen that the default regulation in force (SED-RE approach) is inefficient from an economic point of view, as the NPV is far from the maximum that could be obtained through the ideal approach (IED). For a rated power of 10 kW, the SED-RE approach obtains an NPV that is 27.2% lower than the IED approach. Nonetheless, this percentage difference is gradually reduced as the installed power of the PV panels increases, down to 9.9% for the maximum analysed power of 50 kW. It is worth mentioning that the other option envisaged by the current regulation, in which the members of the self-consumption community agree and optimise the sharing coefficients (note that, as mentioned above, in this approach an optimisation algorithm has been run to obtain the optimal static coefficients for the sharing of both self-consumed energy and generation surpluses), also leads to an economic performance far away from the ideal maximum, ranging from 18.4% lower for a PV power of 10 kW to 4.8% lower for a power of 50 kW. Finally, the alternative approach to those in force in the regulations proposed in this work (PED approach) allows a substantially better utilisation than the previous ones, reaching exactly the maximum possible for small PV panel powers, since all the energy produced by the PV panels is allocated to the members of the self-consumption community. However, for higher powers, the generation surpluses increase, which can be fully attributed to the community members through this approach, resulting in a worse economic performance than the ideal IED approach.

Table 5 shows the evolution of IRR as a function of PV rated power for the different approaches analysed. As can be seen, the highest IRRs are obtained for the lowest levels of installed power. This is because for small PV panel powers, most of the energy generated is used by customers in the form of self-consumed energy, while the higher the power of the panels, the greater the energy surplus and the less profitable the investment in the self-consumption system. It can also be seen in Table 4, the differences obtained in the IRR for the same installed power of the PV panels, being again the SED-RE approach the one with the worst economic performance. It is also noteworthy that, under the current regulatory framework and assuming that neighbours agree on the best possible sharing coefficients (i.e., the SED-NA approach), the IRR for low power PV is very far from the one that would be obtained through the PED and IED approaches. This is a result of the fact that, despite higher utilisation of self-generated energy for reduced power, the fraction of energy that is assigned as surplus has a greater relative weight on the overall volume of self-produced energy, which means that the lower efficiency in the distribution through the SED-RE and SED-NA approaches has a greater impact on the IRR for small PV power.

Fig. 2 shows for the neighbourhood community as a whole, the monthly distribution of grid consumption (GC) energy, self-consumed energy (SCE), as well as the energy surplus (ES) for the four proposed approaches over a year. Similarly, Fig. 3 shows the energy distribution for the whole year according to the analysed approaches. As can be seen,

Table 4
NPV (€) depending on the nominal power of the PV system for each of the analysed approaches.

PV rated power (kW)	Approach			
	SED-RE	SED-NA	PED	IED
10	25627.5	28724.6	35196.5	35196.5
15	34676.0	37769.6	45852.9	45852.9
20	42882.5	45511.1	53971.8	53971.8
25	50340.9	52499.3	60776.0	60776.0
30	57130.0	58914.5	66611.3	66611.3
35	63129.2	64879.9	71783.0	71783.0
40	67980.3	70179.9	76067.8	76604.4
45	71591.9	74629.7	79859.7	80824.8
50	73882.7	78107.1	81681.8	82013.7

Table 5
IRR (€) depending on the nominal power of the PV system for each of the analysed approaches.

PV rated power (kW)	Approach			
	SED-RE	SED-NA	PED	IED
10	25.43	27.79	32.71	32.71
15	23.51	25.09	29.20	29.20
20	22.21	23.23	26.47	26.47
25	21.22	21.87	24.42	24.42
30	20.38	20.82	22.80	22.80
35	19.66	19.96	21.50	21.50
40	19.02	19.25	20.44	20.44
45	18.41	18.61	19.56	19.58
50	17.80	18.03	18.79	18.87

the differences in the energy distribution for the different approaches lie in the degree of utilisation of the energy produced by the PV panels through their economic allocation as self-consumed versus surplus energy. For the IED and PED approaches, the self-consumed energy is maximised (represented by the red bars). While the surplus is minimised (green bars), which in turn makes the economic performance of the installation as high as possible, since the distribution of self-consumed energy within the community is maximised and, therefore, the savings obtained. Although the sale of surplus energy is also an incentive to be taken into account, it is worth noting the significant difference between the market price of surplus energy and the price for energy consumed from the grid. On the other hand, for the SED-RE and SED-NA approaches, there is a notable decrease in the use of energy allocated to self-consumption, increasing the supply of energy from the grid to cover the total consumption of customers and, consequently, growing the amount of surplus energy. This situation leads to a decrease of the possible annual savings obtained and therefore to a worse economic performance of the investment in the self-consumption installation.

Fig. 4 details the results of the distribution of energy consumed from the grid, self-consumed energy and individualised surplus energy, for each of the consumers during the months of February and October, respectively (note that only these two months are shown for simplicity in the presentation of results). It can be seen that under the default regulatory approach SED-RE (represented in the figure by the bars in purple), the self-consumed energy assigned to each customer is always lower than that resulting from the PED approach (bars in clear blue), which consequently leads to the grid consumption of each consumer being

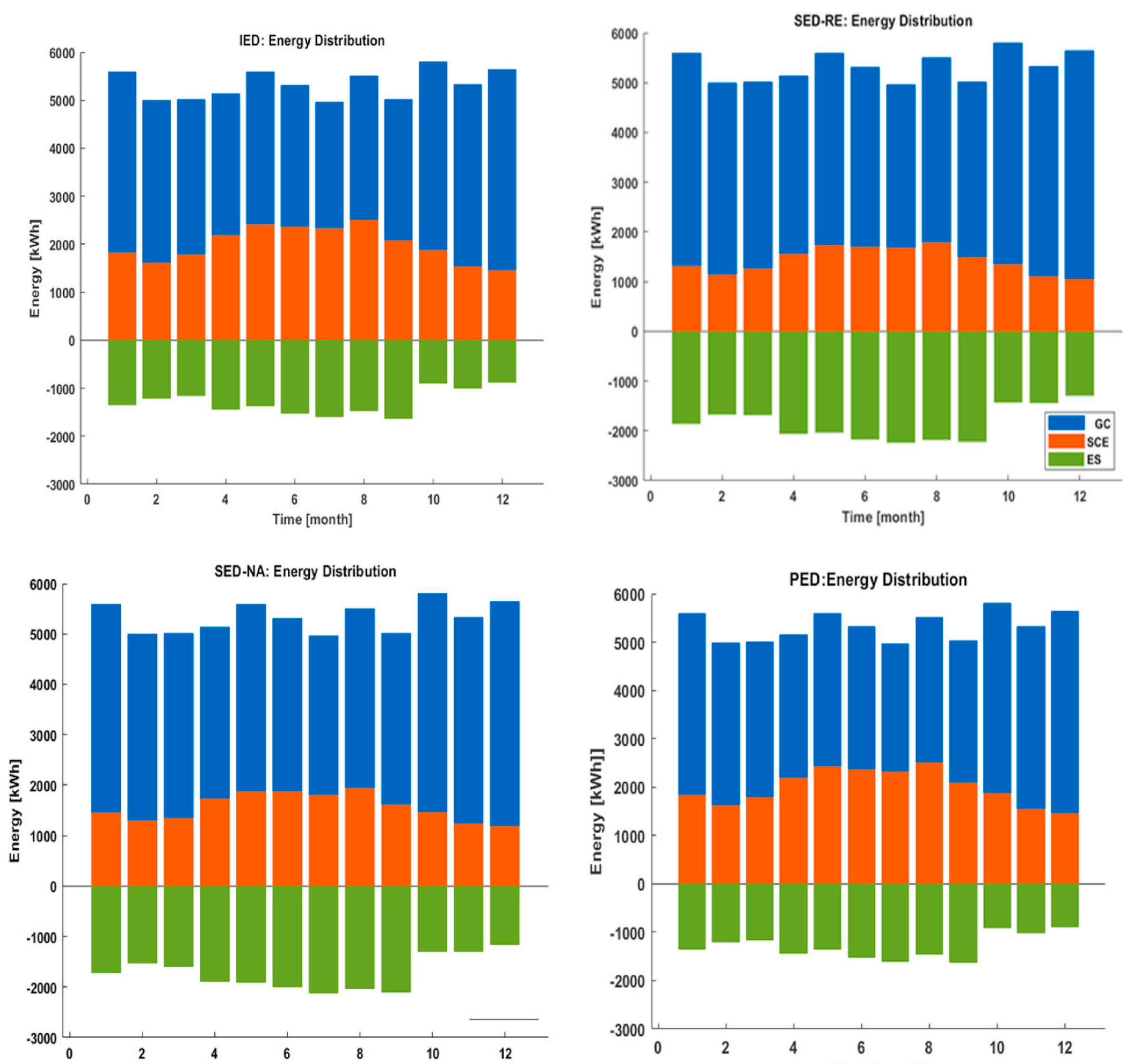

Fig. 2. Monthly distribution of energy consumed from the grid (blue bars). Self-consumed (red bars) and surplus (green bars) over a full year, considering a PV system power of 20 kW. Please note that the total energy consumed corresponds to the red bar plus the blue bar.

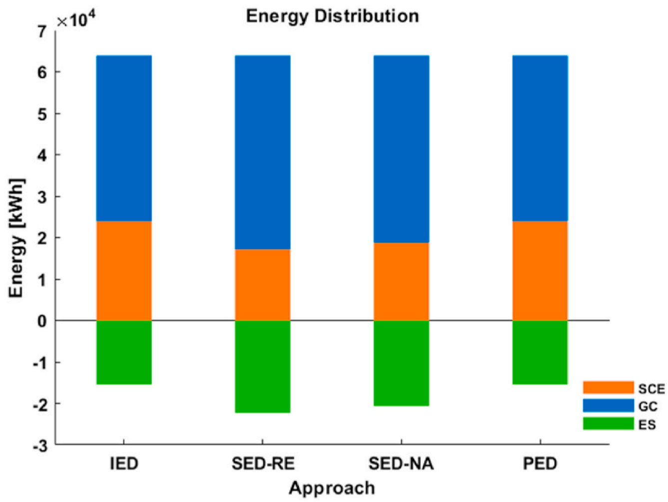

Fig. 3. Annual distribution of energy consumed from the grid (blue bars). Self-consumed (red bars) and surplus (green bars), considering a PV system power of 20 kW.

always higher under the SED-RE approach. These differences tend to be larger for consumers with higher energy consumption, such as customers 4, 5, 7 and 17 (it is also worth mentioning that customer 15 also has a high energy consumption but with a mainly nocturnal consumption profile, so it is less affected by the different self-consumption sharing approaches). This is due to the inefficiency of the default regulatory coefficients, since, for customers with lower consumption, part of the energy from the PV panels that would correspond to them is not used in the hours in which consumption is lower than the individualised self-produced energy, this energy being considered as surplus instead of being reallocated to those customers for whom consumption is higher than the individualised self-consumed energy.

This situation is partially mitigated if instead of using the default allocation coefficients. The optimised coefficients proposed in the SED-NA approach (represented by the yellow bars) are considered. In this case. The joint optimisation of the coefficients leads to some customers significantly improving their individualised self-consumed energy allocation (e.g., customer 14) but to the detriment of the individualised self-consumed energy allocation of other customers (e.g., customers 9 and 15). In any case, it should be noted that, as mentioned above, the SED-NA approach corresponds to an ideal approach that considers perfect information and therefore corresponds to the best possible solution that could be reached under the current regulatory framework. On the other hand, as can be seen in the figure, the proposed alternative approach PED, achieves a better use of self-consumption for all customers by maximising individualised self-consumed energy and, consequently, reducing the energy consumed from the grid of each of them.

4.2. *Sensitivity analysis to the electricity prices evolution*

The results shown above correspond to a baseline scenario in which it has been assumed that the tariff price remains stable throughout the lifetime of the self-consumption project. Therefore, in this section it is proposed to study two alternative prices scenarios assuming two possible future trends of the electricity tariff for consumers: (i) a scenario of an annual increase of the tariff by 3% (inflation scenario) and (ii) another scenario in which an annual decrease of 3% is assumed (depreciation scenario). In this way, the aim is to compare the behaviour of the different approaches analysed against possible future evolutions of the electricity tariff, since this is the aspect that introduces the greatest uncertainty in the study of the economic viability of self-consumption, as a consequence of its direct dependence on the future evolution of the price of electricity in the wholesale markets.

Fig. 5 shows the results of the sensitivity analysis for the approaches

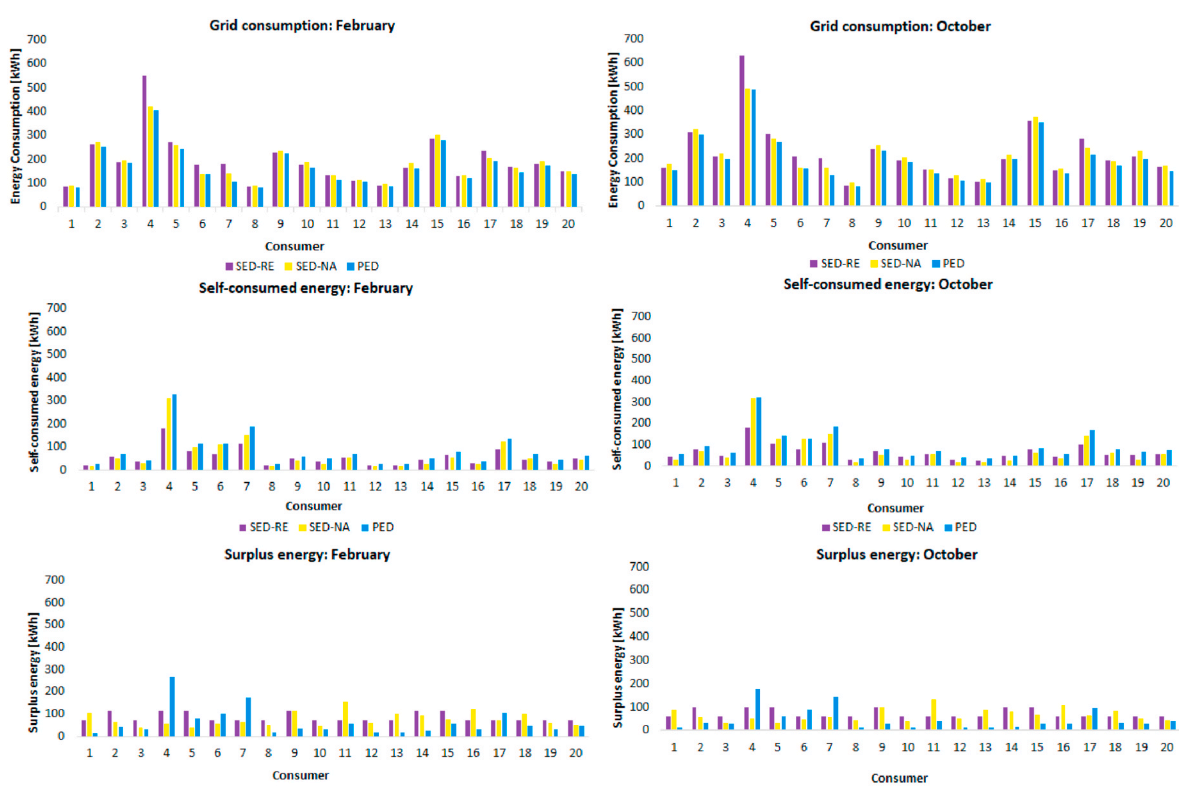

Fig. 4. Energy consumed from the grid (top row), individualised self-consumed energy (middle row) and individualised surplus energy (bottom row) for each of the customers during the months of February (left column) and October (right column).

analysed and the three scenarios mentioned above. As can be seen, the economic profitability of the self-consumption system is higher the higher the annual increase in the electricity tariff, since the greater the savings obtained thanks to the self-consumed energy (with the consequent lower consumption from the grid).

It is also noteworthy that the higher the annual increase in the electricity tariff, the more profitable it is to increase the power of the PV panels (although this increase is attenuated as PV rated power increases), which can be seen in the figure by the steeper slope of the curves corresponding to the scenario of a 3% annual increase in the tariff. This is also due to the fact that the higher the tariff, the more profitable it is to increase the self-consumed energy (by increasing the investment in PV panels) in order to reduce the energy imported from the grid. This increase in NPV by increasing the power of the PV panels is less pronounced for the base scenario and the scenario corresponding to a 3% annual decrease in the tariff. For the latter scenario, a maximum of around 45 kW of installed power is reached, after which it is no longer profitable to increase the power of the panels, as the additional investment in PV panels does not compensate for the incremental value of the savings due to lower consumption of energy imported from the grid. This lower grid consumption also implies that the restriction that does not allow the revenue obtained during a billing period (one month) from the sale of surplus energy to exceed the cost of the energy imported from the grid (as introduced in Section 3.2) is applicable, which makes it no longer profitable to continue increasing the rated power of the PV panels as it is not possible to obtain extra revenue from the sale of the surplus. Please note that the same effect will take place in the other two scenarios (base and electricity price inflation) if the PV rated power continues to be increased above the 50 kW depicted in the figure.

Finally, it is also important to note that the higher the tariff increase, the greater the differences between the different approaches analysed. In other words, the higher the tariff, the more inefficient the investment is under the current regulatory framework, both in its default configuration (SED-RE approach) and under an assumption of optimised sharing coefficients (SED-NA approach).

4.3. Sensitivity analysis to the discount rate

Similarly to the analysis introduced in the previous section, a sensitivity analysis has also been performed on the discount rate, starting from the base scenario (discount rate of 4%) and introducing two alternative scenarios with a discount rate of 2% and 6%, respectively. In this way, the aim is to analyse the economic behaviour of shared self-consumption facilities according to different macroeconomic trends.

Fig. 6 shows the results of the sensitivity analysis performed for different interest rates. As can be seen, the interest rate considered in the analysis has a clear influence on the results obtained on the profitability of the shared self-consumption project. As expected, the higher the interest rate, the lower the profitability of the project, while in the case of low interest rates, considerably higher profitability can be obtained. Analogous to the energy price sensitivity analysis, the lower the interest rate, the greater the difference between the different approaches analysed in this paper. However, it is worth mentioning that in all cases the ideal approach and the alternative approach proposed in this paper outperform the economic returns obtained by the approaches currently available under the current regulatory framework.

5. Conclusion and policy implications

The regulation concerning self-consumption in Spain has evolved significantly in recent years. The entry into force of Royal Decree-Law 15/2018 eliminated different regulatory barriers and laid the foundations of a new regulatory framework for self-consumption, also introducing the modality of collective self-consumption under which different customers can share the same renewable generation system. Subsequently, Royal Decree 244/2019 introduced the conditions on the remuneration regime corresponding to self-consumption, both in its individual and collective modality. However, despite representing a significant advance over the previous regulatory framework, this new regulation introduces a series of inefficiencies with respect to the criteria for sharing the energy produced by the collective generation system. These inefficiencies are associated with an economic cost for the members of the collective self-consumption community, which to a certain extent may discourage its deployment, with the consequent negative impact on the development of renewable energies and the achievement of climate objectives.

Therefore, this paper has carried out a study with the objective of

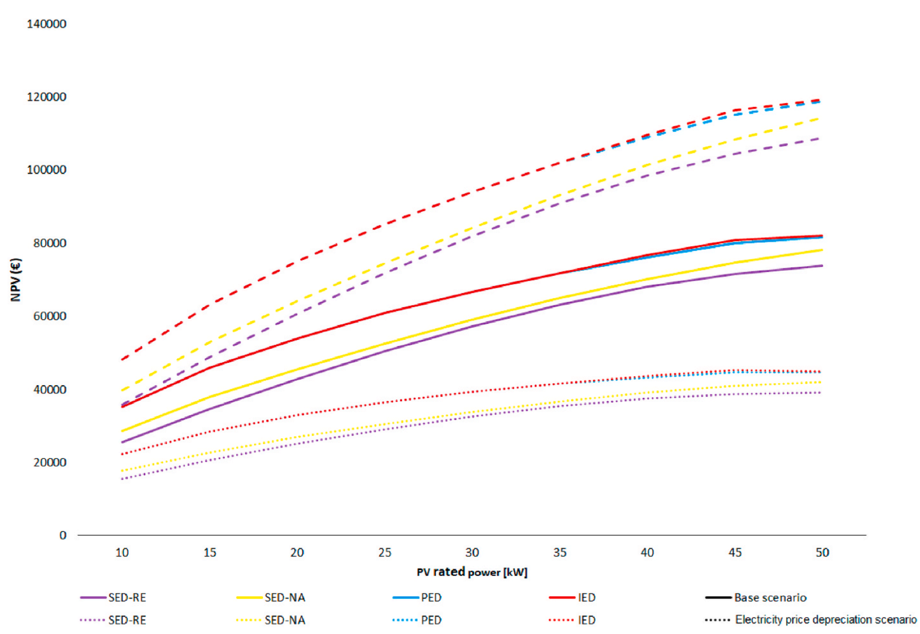

Fig. 5. NPV as a function of PV panel power for the three electricity price scenarios: base scenario (solid lines), 3% annual increase in electricity tariff (dashed lines) and 3% annual decrease in electricity tariff (dotted lines).

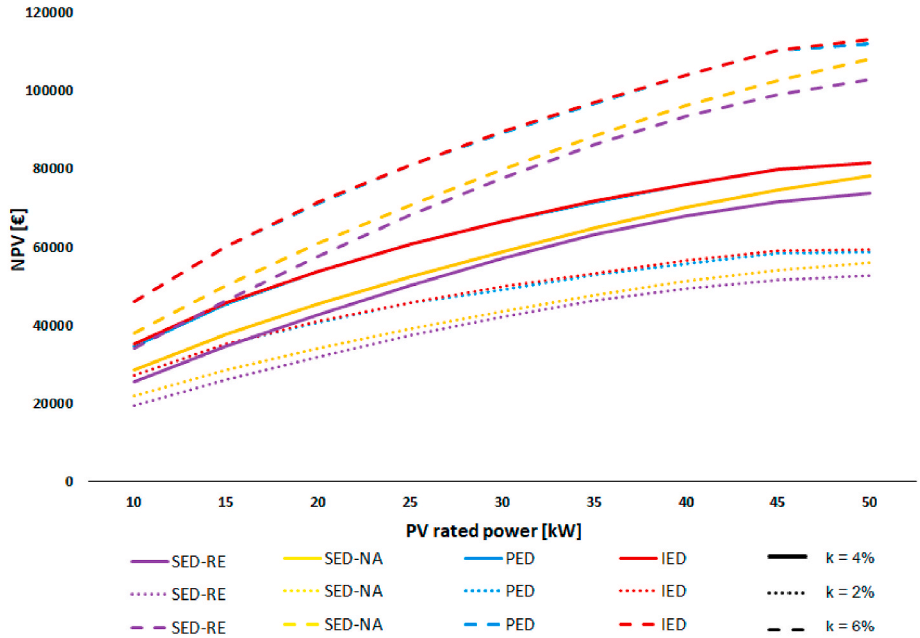

Fig. 6. NPV as a function of PV panel power the three discount rate scenarios: base scenario (solid lines), 6% discount rate (dashed lines) and 2% discount (dotted lines).

quantifying from an economic point of view the inefficiencies existing in the current regulatory framework, as well as proposing other alternative distribution criteria to maximize the economic efficiency of collective self-consumption systems.

The distribution criteria established in Royal Decree 244/2019 are based on fixed coefficients for the allocation of both self-consumed energy and the economic rights of energy surplus. The main advantage of this approach is its great simplicity, since it is simply sufficient for each customer's supplier company to have access to the meter reading of the PV system, as well as that of the customer itself. However, its main disadvantage is that it does not allow the members of the self-consumption community all the economic exploitation that is actually possible. In the results obtained in this work, this inefficiency of the regulatory framework results in a significantly lower net present value than could be obtained if the self-produced energy were ideally distributed among all the neighbours. This difference in NPV varies between 18.4% for the smallest PV system power analysed (10 kW), and 4.8% for the largest power analysed (50 kW). However, it should be noted that the results obtained on the IRR show that the highest profitability is obtained for the lowest PV panel power, precisely for the power levels where the current regulatory framework leads to a higher NPV difference with respect to the theoretical maximum possible.

In view of this situation, this paper proposes an alternative approach consisting of an *ex post* distribution according to the energy actually consumed by each member of the collective self-consumption community. The results obtained show that this approach substantially improves the current regulatory framework, virtually equaling the theoretical maximum that could be obtained if the whole community were considered as a single customer. However, it is worth mentioning that this approach includes an additional complexity, since the supply companies need to have access to the meters of the other customers (not necessarily, all the members of the community have to be supplied by the same company). However, this additional complexity can be easily solved from a technical point of view by means of adequate coordination between suppliers or through the mediation of a coordinating entity. To this end, it is essential to regulate data exchange procedures while ensuring data privacy.

Finally, it is necessary to mention that, as shown in the results section, there is a play of interests between the different consumers, since the economic return on the investment made by each consumer is affected unequally depending on the approach used. This adds further complexity to the task of apportioning responsibilities for the initial investment by each consumer in such a way that this apportionment is carried out as fairly as possible. However, from a regulatory point of view, it would be advisable to enable energy service companies to own and operate the self-consumption plant, selling the energy to the community's customers at an agreed price. In this way, it would facilitate the maximum use of the energy generated by the PV system, at the same time, it would reduce the financial risk of the customers (since the investment would be undertaken by the energy service company itself) and would allow the customers to visualize in advance what the savings obtained by the installation of the self-consumption system would be.

Credit author statement

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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.

Data availability

Data is shared by Mendeley Data Repositor

Acknowledgements

This research was funded by the CERVERA research programme of CDTI, the Industrial and Technological Development Centre of Spain, under the research Project HySGrid+ (CER-20191019), by the Andalusian Government under grant PYC20 RE 078 USE and by the Spanish Ministry of Science and Innovation under grants PID2021-127550OA-I00 and TED2021-131311B–C21.

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