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Analysis and optimisation of collective self-consumption in residential buildings in Spain

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ABSTRACT

Studies on self-consumption in residential use are constantly evolving, and society claims new solutions in response to changes to new paradigms. This paper aims to optimise the sizing of a self-consumption installation for collective self-consumption in a residential building under the Spanish regulatory framework. The study considers the current price volatility in the retail electricity Spanish market and focuses on the techno-economic analysis of self-consumption in a building consisting of 12 dwellings using photovoltaic energy and the possible support of a storage system. The three aspects analysed are the sizing of the self-consumption facility, the use of smart appliances to shift their consumption to more cost-effective times and the sharing of the renewable energy generated by the facility among the consumers participating in the collective self-consumption. This study employs two models, an average-day model and a whole-year model. The techno-economic analysis yields that between the two self-consumption modalities for residential consumption, the modality with surplus simplified compensation is more profitable than the one without surpluses. Finally, the study focuses on sharing the total renewable energy generated among the participants. The results indicate that both ex-ante and ex-post dynamic sharing brings few benefits.

1. Introduction

Many countries worldwide, especially in the European Union, are concerned about growing energy consumption and moving away from fossil fuels towards cleaner energies. The promotion of renewable energies, their efficiency and self-consumption are some of the policies that the European Union is considering strongly in residential energy consumption [1]. Many aspects encourage increasing the level of self-consumption in residential areas. On the one hand, consumers make a more profitable investment, as they benefit from lower electricity bills and a shorter payback period. Through the use of smart appliances (e.g. washing machines, dryers, dish machines, refrigerators, electric water heaters, etc.), it is possible to create a demanding schedule to increase the rate of self-consumption and decrease consumption peaks. Complex and tedious administrative procedures are also being streamlined, thus increasing the competitiveness of small-scale self-consumption projects.

In summary, self-consumption is ideal for supplying energy via distributed or dispersed generation. Its main advantages are the use of renewable energy and the decrease of power losses in distribution networks, among others [2]. Although a hypothetical grid in which self-consumption supplies all the loads is not feasible nowadays, it is essential to highlight that it is a way to encourage consumers to be active in this new paradigm [3].

Studies on self-consumption in residential use continue to evolve, and new solutions are constantly appearing in response to changes in our society. On the one hand, citizens are committed to greater use of renewable energies, assuming the possible added costs. On the other hand, the cost reductions involved in investing in the installation of self-consumption further accelerate its use. Finally, the sharp increase in the cost of electricity bills is providing a final boost so that investment in a self-consumption installation is on the citizen's agenda. Many countries created and are still introducing changes in the regulation of self-consumption for residential and commercial use. In particular, the subsidies introduced successfully incentivised investments in renewable energy for residential use.

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Different economic financing scenarios have demonstrated the economic viability of investment projects in self-consumption installations [4]. One of the first studies in Spain that demonstrated the grid parity of self-consumption was conducted by Talavera et al. [5]. Although they concluded that a lack of regulatory support from the Spanish government and a decrease in reluctance on the part of the major electricity companies, the reality was that regulation was finally approved that went in the opposite direction. In those years, interest in self-consumption was growing, although it was still scarce [6]. Therefore, knowing that regulatory frameworks played a very significant role in the progress of self-consumption, new advances and research were appearing, comparing and evaluating the regulatory frameworks of some countries.

The first projects did not envisage any subsidies. Bertsch et al. [7] and Cucchiella et al. [4] investigated the economic viability of self-consumption in the residential sector in an electricity market scenario without subsidies. They compared internal rates of return in Germany and Ireland, providing a simulation model to determine the most cost-effective sizes of PV and storage systems from a household perspective. Camilo et al. [8] analysed the regulatory framework in Portugal (Decree-Law 153/2014) regarding self-consumption from the point of view of economic profitability. Four different scenarios were studied: (i) separately, all the energy generated is injected into the grid, and all the energy demand is consumed; (ii) the renewable energy generated is consumed, and the surplus is injected into the grid; (iii) the surplus is stored in batteries to be subsequently consumed or injected into the grid, and (iv) the net metering model. Currently, the new framework, outlined in Decree-Law 162/2019 of 25 October, aims to provide a more transparent and supportive structure for self-consumption with renewables, energy storage and energy communities.

Several studies have been carried out regarding the storage of renewable energy generated by photovoltaic panels. Cerino and Noussan [9] demonstrated through a comparison with the net metering framework used in Italy that it is not competitive, mainly due to two factors, the investment cost of the energy storage system and the non-zero efficiency of the charging and discharging cycles of the batteries. Lazzeroni et al. [10] also presented a study on the economic analysis of investment in photovoltaic energy in the residential sector, taking into account the variability of the solar resource across the country's geography case, Italy. In Slovenia, under a net metering framework, Virtič and Kovačič [11] optimised the self-consumption of a business-residential building by correctly sizing the PV generation system; specifically, they minimised the price per kWh. Another interesting study by Roberts et al. [12] in Australia was the impact of using a centralised shared battery system in combination with PV self-consumption and its influence on the electricity bill of an apartment building. The outcome was that using a storage system alone was not convincing, given the investment costs and without subsidies. In another work, Avilés et al. [13] tested Net Billing and Net Metering schemes to microgrids for individual and community residential customers and took into account sixteen geographic locations in Chile. They concluded that communities are more economical than individual dwellings, and concerning geographic location, rural areas were more cost-effective.

Although self-consumption is becoming a reality today, there are some limitations, the most important being the investment cost. Nevertheless, collective self-consumption represents an opportunity to reduce investment costs. For this, creating an appropriate regulatory framework is necessary to promote self-consumption. Frieden et al. [14] analysed and compared the different regulatory frameworks in the EU member states. Simultaneously, Campos et al. [15] concluded that collective renewable energy prosumers should benefit from a regulatory structure that stimulates innovation potential. But at the same time, it guarantees them sufficient legal support, as the current laws for collective self-consumption need to provide a solid legal framework. Therefore, following EU energy policies, countries should set clear and ambitious targets for decentralisation between 2030 and 2050. Recently, Contreras et al. [16] have presented a framework that integrates the long and short-term planning of a collective sharing a solar plus energy storage system by the French regulation. The collective self-consumption consisted of 15 consumers in the south of France.

There have been many regulatory changes in Spain regarding renewable energies. From the generous promotion carried out in 2007 to incentives eliminated in 2014. A related economic and financial study (regulatory cuts) was conducted by Ibarloza et al. [17]. Royal Decree 900/2015 [18] established high taxes and charges (known as the sun tax) that made the installation of self-consumption in a Spanish home not profitable. It was already in the following modification of the law, Royal Decree-Law 15/2018 [19] where the sun tax was derogated, and a whole series of new features were incorporated that would determine the future of self-consumption of electricity. In the current Royal Decree 144/2019 [20], some barriers were abolished [21]. Self-consumption is now a reality using a simplified mechanism to compensate for the economic surplus of not self-consumed energy. On the other hand, it is also in this last Royal Decree that the administrative, technical and financial conditions of collective self-consumption are developed.

As mentioned previously, Talavera et al. [5] studied grid parity and self-consumption before the Royal Decree 900/2015 [18]. In that study, they already discussed the economic problems, the changing regulatory framework, excessive bureaucracy and the addition of extra fees or possible backup tolls, which are very harmful to self-consumption development. The current raised prices are creating a new scenario where the introduction of storage systems is close to being used. Similar results were obtained by López Prol and Steininger [22] on the profitability of the residential, commercial and industrial sectors under the same regulatory framework. They reported that PV generation was economically not viable for users in the residential and industrial sectors. Finally, De la Hoz et al. [23] studied the same problem and concluded that the tariff and a new change in the regulatory framework were needed.

In 2019 the new Royal Decree 144/2019 [20] came out. Since then, several authors have analysed self-consumption in Spain. López Prol and Steininger [24] examined the impact of the new regulation using the internal rate of return as an indicator of profitability in the residential, commercial and industrial sectors. In the same line, Escobar et al. [25], using average data and a financial model, analysed the difference in profitability according to the number of members in a household and compared the results in six EU countries, concluding that the payback period in Spain was more significant than in the rest of countries. Roldan et al. [26] performed an average study taking into account the regulated VPSC (Voluntary Price for Small Customer) tariff, specifically, the 2.0A residential tariff and concluded that the installation of a commercial PV kit of 1.5–2 kWp appeared to be optimal. Based on monitoring a full year of operation of a self-consumption PV plant in a university building, Mendieta and Hernández [27] simulated the building's behaviour. The results determined that grid parity was reached in a payback period of 8 to 9 years in educational and office buildings. Concerning the levelised cost of electricity (LCOE), it was in the market price range of the electricity pool.

In the studies discussed above, average values of hourly energy prices were used for each hour of the year and dwelling demand values. In cases where variability changes abruptly over a long period, such as a year or where the electricity market is highly volatile, these results may be far from reality. Given this, the following studies focus on analysing these circumstances. Gallego et al. [2] conducted a survey of self-consumption performed with DER-CAM in Spain using hourly electricity prices instead of applying constant values related to average market prices. The obtained results showed that self-consumption was cost-effective in all regions in Spain. A new approach in the study of self-consumption in dwellings, such as the influence of the resolution of smart meter reading periods on the electricity consumption profile of homes, was addressed by Jiménez et al. [28]. In that article, the authors indicated that high recording intervals could provide an overestimation of performance metrics.

This paper aims to optimise the sizing of a self-consumption installation for collective self-consumption in a residential building under the Spanish regulatory framework based on a techno-economic analysis. The study focuses on three main aspects: it compares an average daily model with a proposed whole year model, it analyses the effect of the domestic load scheduling, and it evaluates the use of variable sharing coefficients established in the Order TED/1247/2021 [29]. These three aspects comprise the novelty of this paper. Another significant issue is that this study is conducted in the context of the recent volatility of retail electricity prices.

The document is organised by describing, in Section 2, the methodology used, where the domestic load model, the energy management system and the economic evaluation were addressed. The description of the study case and the data in Section 3 follows this, including the irradiance, appliances and electricity price data. Section 4 presents the results of sizing optimisation, scheduling household appliances and the renewable energy sharing problem in the collective self-consumption. Finally, conclusions are provided in Section 5.

2. Methodology

The study focused on a building composed of 12 dwellings, where a collective self-consumption system was analysed from different points of view. The following actions were developed to achieve the main objective of the article:

- Compare the two types of self-consumption (with and without surpluses) between them and versus the installation without self-consumption. At the same time, compare the self-consumption of an individual dwelling versus the collective one.
- Evaluate the convenience of applying the scheduling of household appliances.
- Optimise the sharing coefficients in collective self-consumption.

Firstly, the study was divided into two types of installation, individual (one dwelling) and collective (12 dwellings), and then applying the two modalities of self-consumption following the regulations of Royal Decree 144/2019 [20] (with and without surpluses) to each one. In addition, two models were used; an average daily model and a whole-year model. The use of hourly electricity prices justified the comparison of these two models. Also, the compensation mechanism used in one of the self-consumption modalities raised questions about the accuracy of the average daily model.

Table 1 illustrates a summary of the different scenarios evaluated throughout the study. In this table, the first column splits the study cases into four groups. The first one is the case without self-consumption. This is the case study of reference. The second group corresponds to eight sizing optimisation scenarios depending on dwelling type, self-consumption modality and time model. The third group is divided in three subgroups: sizing and scheduling optimisation, a scheduling strategy based on the irradiance and a scheduling strategy based on the electricity prices. The average daily model was not applied to scheduling. Finally, the sharing of the renewable energy generated is analysed by optimisation, a pro-rata sharing based on power demanded and equal sharing. In this last group, neither the average daily model nor individual dwelling was applied.

From the point of view of optimisation, the objective function for all the analyses was the cost of energy (COE). The algorithm used in this paper to solve the optimisation problems belongs to the group of population heuristics. Among the plethora of meta-heuristics algorithms, JAYA algorithm [30] was chosen because it does not require tuning any algorithm-specific parameters except for the population size and the number of iterations. All the algorithms were programmed in MATLAB® version 2022a.

2.1. Dwelling load model

As mentioned in the introduction to this section, a group of studies to be carried out include the scheduling of dwelling loads. To this end, a model has been designed for each house appliance typically used in dwellings.

In a previous work [31], a simpler model was already used to allow the scheduling optimisation of household loads over time. A more detailed model has been developed in this paper to model the wider variety of appliances and to fit the actual demand curve. Once the various household appliances were studied, three main patterns were found:

1) A train of a few pulses with different widths.
2) Loads with periodically performance, or not being periodic, could be approximated by a periodic function.
3) Constant loads, specifically loads with a low consume and distributed along the day.

Therefore, the proposed model in this paper includes these three functions to allow modelling different household appliance types. Each appliance has a demand model whose load profile can consist of a combination of three functions, one for each pattern. The first two functions are achieved by equation (1).

$$p(t) = \sum_{i=1}^{n} 1/(exp(m(t - t_i + d_i/2)) + 1) - 1/(exp(m(t - t_i - d_i/2)) + 1) \tag{1}$$

The first function models a multi-pulse string with different pulse widths and its start and stop times. Fig. 1a represents this string of pulses where t_i is the centre of the pulse, d_i is the width of the pulse, m is a parameter proportional to the slope of the pulse and n the number of pulses. In addition, the pulse centre and pulse width values are randomly generated from a normal distribution with average values t_i and d_i, and standard deviations σ_{t_i} and σ_{d_i}, respectively. This string of pulses is generating using (1).

The second function (Fig. 1b) consists of a string of pulses of equal width and equally spread over a given time interval. In this case, the periodic pulse string with start at t_{start}, end at t_{end}, width d and n the number of pulses, is again defined by equation (1), being:

$$d = (t_{end} - t_{start})/(n - 1) \tag{2}$$

$$t_i = \{t_{start}, t_{start} + d, t_{start} + 2d, \cdots, t_{start} + (n - 1)d\} \tag{3}$$

Note that the width d_i is calculated from a normal distribution with mean d and standard deviation σ_d.

Table 1
Different scenarios based on dwelling, self-consumption and time model types.

Study cases		Type of dwelling		Self-consumption modality		Time model		Number of scenarios
		Individual	Collective	without surpluses	with surpluses	Average daily model	Whole year model	
Without self-consumption		yes	yes	no	no	yes	yes	2^2
Sizing optimisation		yes	yes	yes	yes	yes	yes	2^3
Sizing and Scheduling	- Optimisation	yes	yes	yes	yes	no	yes	2^2
	- Irrad. strategy	yes	yes	yes	yes	no	yes	2^2
	- Price strategy	yes	yes	yes	yes	no	yes	2^2
Sharing	- Optimisation	no	yes	yes	yes	no	yes	2
	- Pro-rata demand	no	yes	yes	yes	no	yes	2
	- Equal	no	yes	yes	yes	no	yes	2

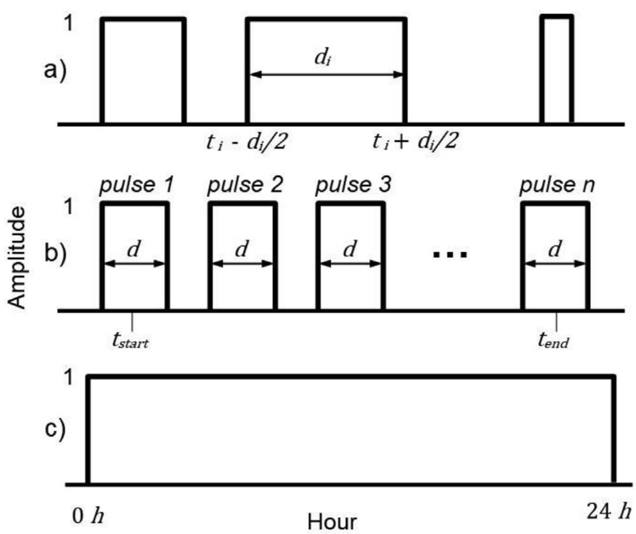

Fig. 1. A) asymmetric string of pulses, b) periodic train of pulses and c) constant function.

The third function corresponds to a constant load for a full day (Fig. 1c). The amplitude of this constant load is generated using a mean value and a standard deviation σ_E.

Most household appliances can be modelled using only the first function, and others using a combination of them. For example, the first function is used for appliances such as electric water heaters, cookers, washing machines, etc. In conjunction with the first function, the second one is used for lighting and refrigerator plus freezer. The third function is used for standby consumption and others. These three functions can be weighted so that the area of the waveform modelled by the appliance is unity. Therefore, the equation that models the pattern of each appliance is:

$$p_{appliance} = E_1 p_1(t) + E_2 p_2(t) + E_3 \quad (4)$$

Where

$$\int_0^{24h} p_1(t)dt = 1, \int_0^{24h} p_2(t)dt = 1 and E_1 + E_2 + E_3 = 1 \quad (5)$$

The daily demand power of each appliance, $p_{appliance}$, is calculated for each day of the year. Although the mean values of the time instants and pulse widths are fixed, each day results in a different demand curve due to the dispersion introduced by the standard deviation of each of them. Once the waveform pattern representing the consumption of each household appliance has been defined, it is necessary to adjust it to average daily consumption. For this purpose, the generation of the pattern of loads is obtained from the summary of basic information on consumption in the residential sector in Spain [32], updated with 2020 data provided by the Institute for Energy Diversification and Saving [33]. Table 2 provides these consumptions per appliance. On the other hand, a daily seasonality coefficient (Table 3) has been obtained from the evolution of annual consumption in an average Spanish household [34,35].

Finally, for the case of collective consumption, a random scaling factor between 75 % and 125 % ($C_{household}$) has been used for each dwelling to diversify consumption. Therefore, the unit area waveform obtained by (4) is affected by a daily amplitude of value formed by three factors o coefficients.

$$E = C_{household} C_{seasonality} C_{appliance} \quad (6)$$

Another aspect to consider is the model of household appliances whose operation can be programmed over time. To this end, this study allows for scheduling household appliances such as the washing machine, dishwasher and tumble dryer. These appliances are modelled using the first function (Fig. 1a), using a single pulse. This way, the instant time it comes into operation can be optimized.

2.2. Energy management system model

The hybrid system used for modelling a single home and collective consumption has the same model. However, there are some differences, especially in the economic analysis. Regarding the energy model, an energy balance is made among the elements that constitute the hybrid system: the renewable energy (PV), the battery, the load and the grid [31]. Fig. 2 presents the simple structure for energy management in the hybrid system. The PV panel is modelled with its generating power (P_{PV}) directly proportional to the irradiance. As for the battery model, the battery is considered an ideal energy reservoir except for charging and discharging energy

Table 2
Average annual consumption per appliance and appliance coefficient.

Appliance	kWh/dwelling and year	$C_{appliance}$
Heating	313.56	0.8591
Water heater	317.94	0.8711
Cooker	395.48	1.0835
Air conditioning	99.37	0.2723
Lights	500.00	1.3699
Refrigerator	804.90	2.2052
Freezer	159.33	0.4365
Washing	311.68	0.8539
Dishwasher	159.32	0.4365
Dryer	88.09	0.2413
Owen	217.25	0.5952
TV	320.58	0.8783
PC	195.26	0.5350
Standby	281.72	0.7718
Rest appliances	92.78	0.2542

Table 3
Seasonal coefficients of residential demand.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$C_{seasonality}$	1.284	1.160	1.015	0.849	0.857	0.870	1.139	0.911	0.891	0.932	0.849	1.243

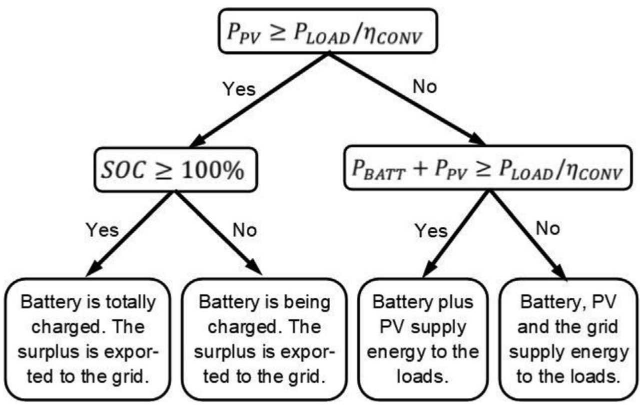

Fig. 2. Energy management scheme for a dwelling.

losses and self-discharge losses. Charging the battery from the grid is not allowed because it is uneconomical.

In the case of collective self-consumption, the hybrid system is centralised, i.e. the battery and the installation of the panels are communal. Therefore, from the point of view of the simulation of the hybrid system, it makes no difference whether it is one or several dwellings. However, when calculating the electricity bill, it is necessary to know how the energy generated by renewable energy is distributed among the different users. In principle, equal sharing was chosen, although different alternatives have been simulated and optimized.

2.3. Economic evaluation

To evaluate the project, it is necessary to simulate the system for one year. The case study is intended to study the profitability of the installation over a more extended period, e.g. fifteen years. Therefore, all the costs and revenues incurred during the remaining years are accounted for, considering the analysis of one year but introducing the effect of the interest rate and inflation.

The costs involved in installing a hybrid system include equipment investment, replacement and maintenance costs. These costs will deduct the income from the sale of electrical energy and the installation equipment's salvage value, which is shorter than the project's lifetime.

The investment costs will be incurred at the beginning of the study period, corresponding to purchasing and installing the elements that compose the hybrid system. These costs will be a function of the installation (P_{SIZE}^{PV},C_{SIZE}^{BATT} and P_{SIZE}^{CONV}), and (7) shows their detail.

$$C_{INV} = C_{INV}^{PV}P_{SIZE}^{PV} + C_{INV}^{BATT}C_{SIZE}^{BATT} + C_{INV}^{CONV}P_{SIZE}^{CONV} + C_{INSTALL} \tag{7}$$

During the project's life, it is necessary to add the different variable costs that the project incurs. As they occur in the future, these costs must be discounted to the present value at the time of installation. Since the battery life is usually shorter than the project's life, the battery replacement's investment ($C_{REPLACE}^{BATT}$) and the salvage value at the end of the installation ($V_{SALVAGE}^{BATT}$) must be affected by the appropriate discount rate. The electricity bill (C_{ELEC}) will also be considered a cost since although it may decrease due to the sale of energy to the grid, it will never be negative. The sum of all costs or capital flows discounted to the initial date of the facility is known as the net present cost (8).

$$NPC = C_{INV} + C_{REPLACE}^{BATT}\sum_{r=1}^{n_R}\frac{1}{(1+i_r)^{r\cdot LIFE_{BAT}}} - V_{SALVAGE}^{BATT}\frac{1}{(1+i_r)^n} + C_{O\&M}\sum_{k=1}^{n}\frac{1}{(1+i_r)^k} + C_{ELEC}\sum_{k=1}^{n}\frac{1}{(1+i_r)^k} \tag{8}$$

The discount factor is defined by (9) and depends on the real interest rate (i_r) and the number of years (n), which in turn depends on the nominal interest rate (i) and the inflation rate (f).

$$f_d = \frac{1}{(1+i_r)^n} \tag{9}$$

$$i_r = \frac{i-f}{1+f} \tag{10}$$

The approach to calculating the battery replacement cost and the salvage value is the same, except that it relates to specific points in the project's life. For this purpose, the number of replacements (11) and the salvage value (12) are calculated in advance.

$$n_R = int\left(\frac{LIFE_{PROJECT}}{LIFE_{BATT}}\right) \tag{11}$$

$$V_{SALVAGE}^{BATT} = C_{REP}\frac{LIFE_{BATT} - (LIFE_{PROJECT} - n_R LIFE_{BATT})}{LIFE_{BATT}} \tag{12}$$

The last cost to assess is the cost of electricity purchased from the grid (13). This cost will also be affected by the discount rate and its development will be explained in the following subsection. It should be noted that this cost is calculated independently for each dwelling, being (n_h) the number of households.

$$C_{ELEC} = \sum_{j=1}^{n_h} E_{BILL}(j) \tag{13}$$

Once the net present cost of all capital flows over the project's life has been calculated, a hypothetical constant annual cost is calculated. Expression (15) uses the capital recovery factor and the annualised cost for this purpose.

$$CRF = \frac{1}{\sum_{k=1}^{n}\frac{1}{(1+i_r)^k}} \tag{14}$$

$$C_{ANNUALIZED} = NPC \cdot CRF \tag{15}$$

Finally, to assess the actual cost of energy (COE), the annualised cost is divided by the energy consumed during one year.

$$COE = \frac{C_{ANNUALIZED}}{kWh\ demanded\ per\ year}\left[\frac{€}{kWh}\right] \tag{16}$$

Table 4 lists the parameters used in the techno-economic formulation described above.

2.3.1. Electricity tariff analysis

In Spain, there are two ways for small consumers to access electricity supply. Two companies are in charge of that, the reference retailers and the free market retailers. Currently, the number of reference retailers in Spain is 8, while in the free market case, there

Table 4
Parameters for techno-economic studies.

Parameter	Value	Description
C_{INV}^{PV}	544 €/kWp	PV investment cost
C_{INV}^{BATT}	668 €/kWh	Battery investment cost
$C_{REPLACE}^{BATT}$	534 €/kWh	Battery replacement cost
n_R	8 years	Battery Life
C_{INV}^{CONV}	180 €/kW	Inverter cost PV
C_{INV}^{CONV+}	634 €/kWh	Inverter cost PV + BATT
$C_{INSTALL}$	2300 €	Installation cost (legalisation included)
$C_{O\&M}$	$0.02C_{INV}$	Operation and maintenance cost (percentage of total investment cost)
η_{BATT}	0.8	Battery efficiency (controller included)
η_{CONV}	0.93	Inverter Efficiency
i	1 %	Nominal interest rate
f	5 %	Inflation rate
n	15 years	Project life

are more than 300, being their scope local, regional or national. In this work, the tariff used for the tests has been the regulated market price, fixed by the government, which is called the voluntary price for small consumers (PVPC). The PVPC is designed for domestic use or businesses that do not need to take out more than 15 kW of electrical power. This tariff can only be taken out with hourly discrimination in three periods. Table 5 shows the different periods, tolls, charges and taxes for this tariff named 2.0 TD.

Generally, two terms comprise the electricity bill; the fixed (power) term due to transmission and distribution tolls plus charges and the variable (energy) term. The summation of the hourly energy price multiplied by the power demanded in an hour during a specific period, such as a month, forms the variable energy term.

Nowadays, because of the enormous energy cost increase, the electricity bill has a relevant impact on the assessment of a renewable energy installation. This impact is caused by the energy price increase itself and how the electricity bill is determined. For instance, in 2020, the variable (energy) term percentage versus the fixed (power) term was 60 % versus 30 %. However, for the last twelve months (from August 2021 to July 2022), the proportion has increased to 83 % versus 11 %.

Regarding self-consumption, two modalities are regulated by Royal Decree 144/2019 [20].

(i) Self-consumption without energy surplus. The whole energy produced by the installation is consumed or stored without being able to supply the energy to the grid.
(ii) Self-consumption with energy surplus (up to 100 kW). The renewable energy generated can be consumed, stored or supplied to the grid. In this modality, there are two possibilities:

(a) Compensate the energy consumed by the energy supplied to the grid. This mechanism consists of subtracting from the bill the amount obtained by multiplying the hourly exported energy to the grid by the compensation price of energy (this price is lower than the PVPC price, around 68 % of it on average). However, there is a restriction on compensating; this must be done in a month, and the compensation in a month cannot be negative.
(b) Sell the energy exported to the market. This case is not appropriate for smaller consumers, so this case is not considered in this study.

The cases considered in this paper are modalities (i) and (ii-a). The calculation of the electricity bill for a 30-day month corresponds to the following expressions, valid for both modalities by simply assigning a zero value to the compensation value:

$$E_{BILL} = \underbrace{30F_{P12}PC_{12} + 30F_{P3}PC_3 + 30F_{FTM}PC_1}_{Fix\ Term} + \underbrace{\sum_{h=1}^{720} P_{PVPC}(h)E_{imported}(h) - V_{compensation}}_{Variable\ Term} + T_E + C_R + VAT \quad (17)$$

$$TC_{energy} = \sum_{p=1}^{3} E(p)F_{energy}(p) \quad (18)$$

$$V_{compensation} = \min\left(\sum_{h=1}^{720} P_{COMP}(h)E_{exported}(h), \sum_{h=1}^{720} P_{PVPC}(h)E_{imported}(h) - TC_{energy}\right) \quad (19)$$

Where; F_{P12} and F_{P3} are the power fees for transmission and distribution tolls plus charges for peak-flat and valley periods, respectively. F_{FTM} is the fee for the fixed trading margin. PC_{12} and PC_3 are the contracted power for the peak-flat and valley periods. A value of 20 % higher than the maximum power consumed during a year have been considered for the two periods. $P_{PVPC}(h)$ is the hourly voluntary price for small consumers and $P_{COMP}(h)$ is the hourly price of compensated energy exported to the grid. Both values were obtained from [36]. $E_{imported}$ and $E_{exported}$ are the hourly energies imported and exported to the grid. $F_{energy}(p)$ is the energy fees for transmission and distribution tolls plus charges for peak, flat and valley periods, being p the index used to assign the three periods (peak, flat and valley). TC_{energy} is the total energy fee due to transmission and distribution tolls plus charges. $V_{compensation}$ is the compensation value that subtracts from the price of energy imported from the grid after deducting energy tolls. T_E is the electricity tax, C_R is the rental price of the measuring equipment, and VAT is the value-added tax, in this case, 5 %. Table 5 shows the values used in the paper.

Table 5
Fees, Tolls and charges for tariff 2.0 TD.

Term	Value
F_{P12}	26.164043 €/kW·year
F_{P3}	1.143132 €/kW·year
F_{FTM}	3.113 €/kW·year
$F_{energy}(1)$	0.074409 €/kWh
$F_{energy}(2)$	0.02847 €/kWh
$F_{energy}(3)$	0.003034 €/kWh
T_E	0.5 % of fix term plus variable term.
C_R	0.81 €/month

3. Case study data

In this section, all data needed to perform the simulations and optimisations are described. Although there are several cases and many scenarios (see Table 1), all of them share the same initial data: the irradiance, the load and the energy prices.

3.1. Irradiance data

The irradiance data covers one year, in particular from July to June. In Fig. 3, the global irradiance used in this study is plotted for each day of the year and each hour of the day (time step of 5 min) for the scenarios where a full year is analysed, taking into account seasonality. It can be observed from this image that the central area has more areas with low irradiance because it corresponds to the winter season, while at the extremes, it is summer.

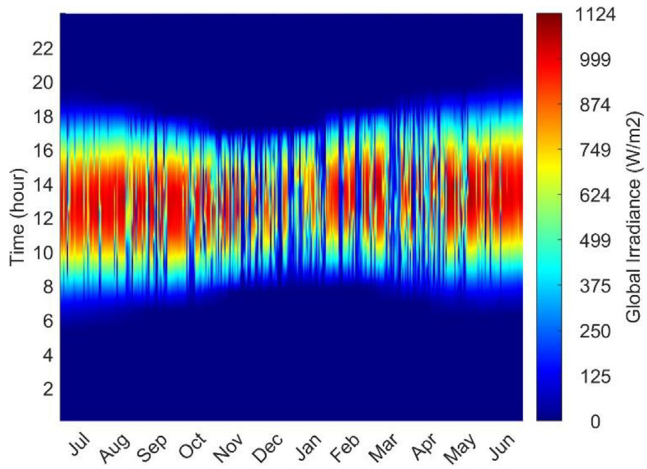

Fig. 3. Global irradiance for a year.

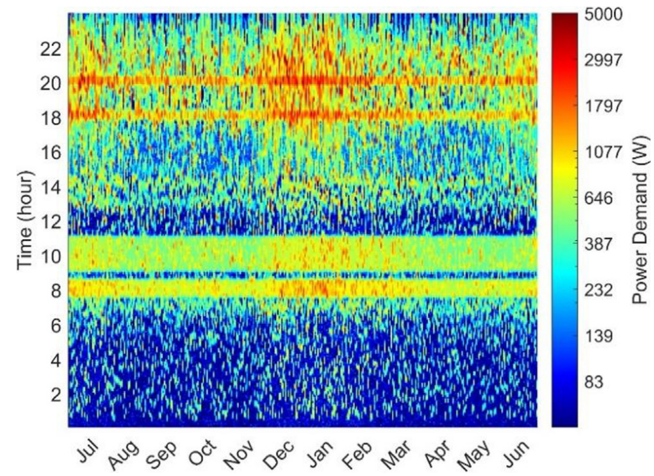

Fig. 4. Power demand of one dwelling for a year.

The irradiance hourly data was obtained from PVGIS photovoltaic geographical information system [37], and corresponds to the years 2019–2020.

3.2. Dwelling domestic load data

A group of 12 household appliances, for which the average annual demand per household is known, has been used to obtain the household loads [32,33].

The parameters (average times and standard deviation) necessary for the model proposed in Section 2 were determined for each appliance. Depending on the particular characteristic of each appliance, the different types of signals have been used, adding them or not, to obtain a profile suitable for typical use in a household. Table 6 lists all the parameters used to model the household loads for each appliance.

Fig. 4 shows the power demand of a dwelling for one year. The horizontal axis represents the 365 days from July to June, and the vertical axis represents the time of day, taken every 5 min. Therefore, the image (its colour) reports the power demand in watts. In the case of collective consumption, a different demand is generated for each of the dwellings considering a random variation as indicated in Section 2.1. In the case of an analysis using the average model for one day, the model consists of an average daily load curve for each dwelling, as depicted in Fig. 5.

3.3. Electricity energy prices

In 2020, electricity prices were low compared to previous years. The cause was, evidently, the covid-19 pandemic, which contracted the economy and consequently reduced energy demand, leading to a fall in prices. In January 2021, there was a temporary increase, mainly due to storm Filomena.

In June 2021, a new electricity tariff came into force, with three different energy prices according to three-time slots: peak, flat, and valley. On 16 September 2021, Royal Decree-Law 17/2021 on urgent measures to alleviate the impact of the increase in natural gas prices on the retail gas and electricity Markets came into force. Fig. 6 shows that price volatility decreased, especially in the peak period, achieving a lower average value in the short term, but then

Table 6
Parameters for household appliances.

Name	Enable	Var.	Function 1						Function 2					Function 3	
			t_i	σ_{t_i}	d_i	σ_{d_i}	E_1	n_2	t_{start}	t_{end}	d	σ_d	E_2	σ_E	E_3
Heating	True	False	19.5	0.5	7	0.5	1	0	0	0	0	0	0	0	0
Water heater	True	True	8	0.5	1	0.1	2/3	1	20	20	0.5	0.5	1/3	0	0
Cooker	True	False	8	0.5	0.16	0.06	0	0	0	0	0	0	0	0	0
			14.5	1	0.6	0.41									
			18	0.5	0.16	0.06									
			21.5	1	0.16	0.47									
Air conditioning	True	False	18.5	0.5	7	0.5	1	0	0	0	0	0	0	0	0
Lights	True	False	7.5	0.5	1	0.2	0.13	15	5	23.5	8/60	0.01	0.1	0.1	0.1
			21	0.5	3.75	0.5	0.67								
Refrigerator	True	False	14	0.1	0.5	0.1	0.1	20	0.5	23.5	0.3	0.01	0.9	0	0
Freezer	True	False	7	0.1	0.4	0.1	1/3	0	0	0	0	0	0	0	0
			13	0.1	0.4	0.1	1/3								
			18	0.1	0.4	0.1	1/3								
Washing machine	True	True	10	0.5	2	0.5	1	0	0	0	0	0	0	0	0
Dishwasher	True	True	16	0.5	3	0.1	0.5	0	0	0	0	0	0	0	0
Dryer	True	True	18	0.5	0.5	0.1	1	0	0	0	0	0	0	0	0
Owen	True	False	21	0.5	0.5	0.1	1	0	0	0	0	0	0	0	0
TV	True	False	8	0.5	0.5	0.1	1/11	0	0	0	0	0	0	0	0
			15	0.5	1	0.1	2/11								
			21	0.5	4	0.1	8/11								
PC	True	False	19	0.5	1	0.1	1	0	0	0	0	0	0	0	0
Standby	True	False	0	0	0	0	0	0	0	0	0	0	0	0.1	1
Rest of appliances	True	False	0	0	0	0	0	0	0	0	0	0	0	0.2	1

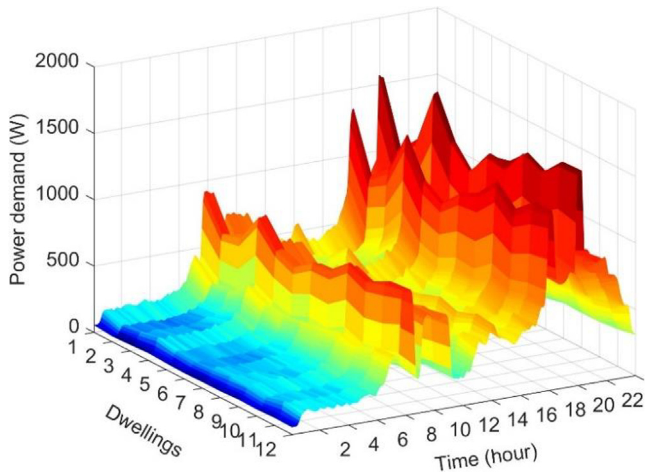

Fig. 5. Average hourly power demand of each dwelling.

suffered large ups and downs, reaching an all-time high on 8 March 2022. Since then, the average price has remained within a more or less constant range. However, one effect observed since mid-June 2022 is the gap between the PVPC price and the price used for the energy compensation surplus fed into the grid. This difference has the effect of increasing the size of the installation to compensate for the cost of energy.

4. Results

This article carried out different analyses. Firstly, the authors studied the optimal sizing of the battery and the photovoltaic panel for the two modalities of self-consumption and both individual and collective self-consumption. In this first optimisation, two models of the system to be studied were used, a simple one based on average values for one day (average day model) and another one that evaluated the system for a whole year (whole year model). Both models used a simulation time step of 5 min. Secondly, the authors carried out a study of the effect of scheduling the demand of certain appliances. They added optimisation of the start time of some household appliances and the incorporation of a strategy for scheduling appliances. Finally, and only for collective self-consumption, the distribution of renewable energy between the different consumers was optimised and analysed. In all optimisation problems, the objective function was the cost of energy (COE).

4.1. Without self-consumption case study simulation results

To evaluate the two modalities of self-consumption, apart from comparing them with each other, they were compared to the installation without self-consumption, assessing their profitability according to the cost of energy (COE). In the case of an installation without self-consumption, the energy cost is none other than the average cost per kWh. Therefore, the installation's annualised cost coincides with the cost of the electricity bill. It is enough to divide the cost of the electricity bill by the energy consumed to obtain the COE. Table 7 shows the simulation results for a single dwelling using the two proposed models (average day and whole year models), and Tables 8 and 9 show the same information but for the case of a building with 12 dwellings using the model for a whole year and the model for an average day, respectively. These tables show the cost of the electricity bill (Annual bill), the net present cost (NPC), the annualised cost (Ann. Cost), the energy demanded in a year (Energy) and the cost of energy (COE) for each dwelling. The last row of Tables 8 and 9 is the sum of the entire set, except for the COE.

Analysing the results obtained, although they are different in electricity bills, the actual bill (whole year model) is 1.02 % higher on average than the bill calculated with the average day values (average day model). The error in the calculation of the COE is also around 1.02 %. Therefore, based on the data obtained, it is much more efficient to use an average day model versus the whole year model for the case of electricity bill calculation without self-consumption due to computational effort.

4.2. PV and battery size optimisation

Given the small error obtained in the results offered by the average day model in the calculation of the cost of energy, in this section, dedicated to the optimisation of the sizing of the self-consumption installation, the optimisation of a single dwelling with the two models (average day and whole year models) was addressed first. Table 10 shows the results obtained for one dwelling using the two modalities of self-consumption.

The first two rows of Table 10 correspond to the self-consumption modality without surplus. According to the results, the solution given by the average day model differs significantly from the solution of the whole-year model. The results yield not only different energy costs but also different dimensioning values of the installation. In addition to installing a 2.3 kWp panel, a battery with a capacity of 5.98 kWh is needed. These results are not at all realistic since when simulating the installation with these val-

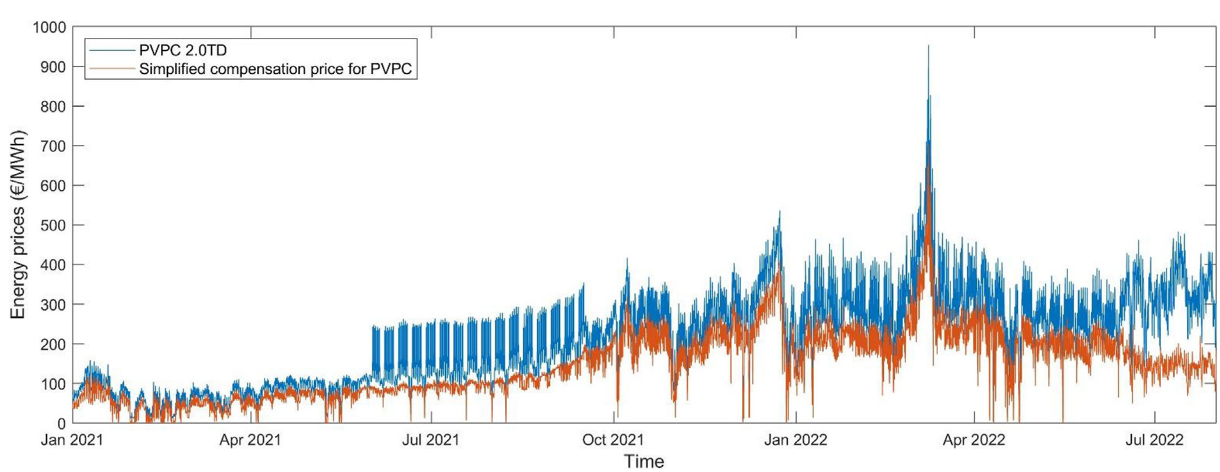

Fig. 6. PVPC 2.0TD and simplified compensation price of energy surpluses.

Table 7
Results for one dwelling using the average day and whole year model.

Model	Annual bill (€)	NPC (€)	Ann. Cost (€)	Energy (kWh)	COE (€/kWh)
day	1578.54	19666.60	1578.54	4361.95	0.36189
year	1595.62	19879.37	1595.62	4361.95	0.36580

Table 8
Results for 12 dwellings (whole year model).

Dw.	Annual bill (€)	NPC (€)	Ann. Cost (€)	Energy (kWh)	COE (€/kWh)
1	1606.60	20016.10	1606.60	4400.00	0.36514
2	1171.02	14589.33	1171.02	3072.86	0.38108
3	1308.09	16297.10	1308.09	3439.05	0.38036
4	1600.70	19942.59	1600.70	4474.91	0.35770
5	1366.06	17019.32	1366.06	3692.65	0.36994
6	1245.65	15519.12	1245.65	3324.52	0.37468
7	1441.47	17958.84	1441.47	3774.00	0.38195
8	1451.05	18078.19	1451.05	3854.00	0.37650
9	1598.51	19915.38	1598.51	4396.09	0.36362
10	1467.27	18280.32	1467.27	4066.97	0.36078
11	1636.38	20387.18	1636.38	4435.41	0.36894
12	1650.42	20562.07	1650.42	4506.33	0.36624
All	17543.21	218565.53	17543.21	47436.79	0.36982

Table 9
Results for 12 dwellings (average day model).

Dw.	Annual bill (€)	NPC (€)	Ann. Cost (€)	Energy (kWh)	COE (€/kWh)
1	1588.56	19791.42	1588.56	4400.00	0.36104
2	1159.55	14446.50	1159.55	3072.86	0.37735
3	1294.00	16121.52	1294.00	3439.05	0.37627
4	1584.23	19737.45	1584.23	4474.91	0.35403
5	1352.38	16848.90	1352.38	3692.65	0.36624
6	1233.03	15361.97	1233.03	3324.52	0.37089
7	1428.61	17798.64	1428.61	3774.00	0.37854
8	1435.64	17886.20	1435.64	3854.00	0.37251
9	1580.77	19694.33	1580.77	4396.09	0.35958
10	1453.31	18106.36	1453.31	4066.97	0.35734
11	1619.58	20177.82	1619.58	4435.41	0.36515
12	1634.09	20358.60	1634.09	4506.33	0.36262
All	17363.75	216329.71	17363.75	47436.79	0.36604

Table 10
Sizing results for a single dwelling (average day and whole year models).

Case	Annual bill (€)	NPC (€)	Ann. Cost (€)	Energy (kWh)	COE (€/kWh)	Battery Size (kWh)	PV Size (kWp)
Without surplus (whole year model)	1172.86	19368.67	1554.63	4361.95	0.35641	0.00	2.08
Without surplus (average day model)	230.30	15204.84	1220.42	4361.95	0.27979	5.98	2.30
With surplus (whole year model)	416.13	12023.70	965.08	4361.95	0.22125	0.00	4.39
With surplus (average day model)	348.26	9999.13	802.58	4361.73	0.18401	0.00	3.08

ues with the whole year model, the results obtained are a COE equal to 0.3856 €/kWh, an annual bill of 691.85 €, an NPC of 20955.0 € and an annualised cost of 1682.0 €. Therefore, using the average day model for the self-consumption modality without surpluses is inappropriate. On the other hand, in the case of self-consumption with surpluses under compensation, although the results are not similar, the error is much smaller. However, it is a very high error, 32.5 % and 16.8 % lower in estimating the panel size and COE.

Tables 11 to 14 show the same result but for the collective consumption installation, consisting of 12 dwellings for the two self-consumption modalities and the two-time models of the system. Each row of these tables shows the information for each dwelling and the total in the row labelled 'Coll'. The last row indicates the values obtained in the sizing optimisation. The optimisation results for the whole-year model (Tables 11 and 12) were a 22.53 kWp and 0 kWh for self-consumption without surpluses and a 45.56 kWp and 0 kWh for self-consumption with surpluses under compensation. The average day model (Tables 13 and 14) yielded a result of 24.04 kWp and 56.78 kWh for self-consumption without energy surpluses and 38.05 kWp and 0 kWh for self-consumption with surpluses under compensation. Concerning the models used, there is undoubtedly a difference between the average day model and the whole year model, and the same considerations are valid in the case of collective self-consumption; that is, the average day model is not appropriate. Therefore, considering only the results of the whole-year model, the COE in a self-consumption installation is generally reduced compared to a non-self-consumption installation.

In the case of a single dwelling self-consumption and a whole-year model, the results (Table 10) show a reduction in the COE value of 2.56 % for self-consumption without surpluses and 39.51 % for self-consumption with surpluses; both compared to an installation without self-consumption (Table 6). According to

Table 11
Size optimisation results under self-consumption without surplus (whole year model).

Dw.	Annual bill (€)	NPC (€)	Ann. Cost (€)	Energy (kWh)	COE (€/kWh)
1	1196.68	16846.77	1352.21	4400.00	0.30732
2	846.09	12478.89	1001.62	3072.86	0.32596
3	958.47	13879.05	1114.00	3439.05	0.32393
4	1184.17	16690.93	1339.70	4474.91	0.29938
5	1000.43	14401.82	1155.96	3692.65	0.31304
6	902.68	13183.96	1058.21	3324.52	0.31831
7	1070.84	15279.03	1226.37	3774.00	0.32495
8	1070.75	15277.88	1226.28	3854.00	0.31818
9	1187.99	16738.52	1343.52	4396.09	0.30562
10	1076.73	15352.37	1232.26	4066.97	0.30299
11	1221.97	17161.87	1377.50	4435.41	0.31057
12	1239.87	17384.95	1395.41	4506.33	0.30965
Coll.	12956.67	184676.05	14823.06	47436.79	0.31248
Battery Size: 0 kWh			PV Size: 22.53 kWp		

Table 12
Size optimisation results under self-consumption with surplus (whole year model).

Dw.	Annual bill (€)	NPC (€)	Ann. Cost (€)	Energy (kWh)	COE (€/kWh)
1	465.82	9476.30	760.62	4400.00	0.17287
2	306.30	7488.90	601.10	3072.86	0.19562
3	361.99	8182.78	656.79	3439.05	0.19098
4	450.06	9280.01	744.86	4474.91	0.16645
5	366.62	8240.43	661.42	3692.65	0.17912
6	326.49	7740.41	621.29	3324.52	0.18688
7	423.88	8953.78	718.68	3774.00	0.19043
8	414.80	8840.73	709.60	3854.00	0.18412
9	458.78	9388.59	753.58	4396.09	0.17142
10	391.19	8546.54	685.99	4066.97	0.16867
11	494.48	9833.33	789.27	4435.41	0.17795
12	493.87	9825.81	788.67	4506.33	0.17501
Coll.	4954.29	105797.63	8491.87	47436.79	0.17901
Battery Size: 0 kWh			PV Size: 45.56 kWp		

Table 13
Size optimisation results under self-consumption without surplus (average day model).

Dw.	Annual bill (€)	NPC (€)	Ann. Cost (€)	Energy (kWh)	COE (€/kWh)
1	431.93	13379.26	1073.89	4400.00	0.24407
2	260.21	11239.92	902.17	3072.86	0.29359
3	291.24	11626.49	933.20	3439.05	0.27136
4	427.27	13321.29	1069.24	4474.91	0.23894
5	271.16	11376.35	913.13	3692.65	0.24728
6	259.88	11235.78	901.84	3324.52	0.27127
7	326.03	12059.91	967.99	3774.00	0.25649
8	315.88	11933.41	957.84	3854.00	0.24853
9	423.47	13273.85	1065.43	4396.09	0.24236
10	301.07	11748.96	943.03	4066.97	0.23188
11	462.28	13757.40	1104.24	4435.41	0.24896
12	477.16	13942.81	1119.12	4506.33	0.24834
Coll.	4247.58	148895.42	11951.12	47436.79	0.25194
Battery Size: 56.78 kWh			PV Size: 24.04 kWp		

collective installation self-consumption and a whole-year model, the results (Tables 10 and 11) show a reduction in the COE value of 15.5 % for self-consumption without surpluses and 51.5 % for self-consumption with surpluses under compensation. These results were compared to an installation without self-consumption (Table 7).

Regardless of the modality of self-consumption chosen, note that the COE presents a lower value in the case of collective consumption than that obtained for individual consumption. Regarding the modality of self-consumption, self-consumption with the sale of surpluses presents a lower COE than self-consumption without surpluses.

Another particularity is that the size of the collective installation is smaller on average than the size of the individual installation, allowing a lower investment cost per dwelling than the individual one. As in the case of the installation of a single house, in the case of collective self-consumption, installing a battery is not profitable. Finally, note that installing a battery is not economically profitable in the optimisation process. Several aspects are responsible for this result. On the one hand, the selling prices of energy are lower than the purchase prices; on the other hand, the charging and discharging energy losses of the battery affect the system efficiency; thirdly, the monthly compensation ceiling and finally, the price of the batteries.

4.3. Sizing and scheduling

In this section, the time scheduling optimisation of certain household appliances was used to evaluate the impact on the energy cost. Table 6 shows the appliances considered, where their

Table 14
Size optimisation results under self-consumption with surplus (average day model).

Dw.	Annual bill (€)	NPC (€)	Ann. Cost (€)	Energy (kWh)	COE (€/kWh)
1	348.91	7453.98	598.30	4418.58	0.13540
2	289.94	6719.33	539.33	3086.86	0.17472
3	321.99	7118.59	571.37	3453.76	0.16544
4	323.08	7132.19	572.47	4493.81	0.12739
5	309.69	6965.44	559.08	3713.18	0.15057
6	293.49	6763.62	542.88	3334.67	0.16280
7	362.34	7621.30	611.72	3774.71	0.16206
8	348.44	7448.19	597.83	3884.98	0.15388
9	342.12	7369.40	591.51	4407.03	0.13422
10	305.84	6917.47	555.23	4093.89	0.13562
11	392.03	7991.25	641.42	4457.33	0.14390
12	376.89	7802.56	626.27	4528.04	0.13831
Coll.	4014.76	87303.31	7007.42	47646.85	0.14707
Battery Size: 0 kWh			PV Size: 38.05 kWp		

switching on was optimised or managed to reduce energy costs. These appliances were the electric water heater, the washing machine, the tumble dryer and the dishwasher. In this study, some ideas were analysed. Firstly, the start time of the four appliances for the twelve dwellings was optimised. Although these variables should be optimised hourly, the number of variables for this problem would have been very high, four variables times 12 dwellings times 365 days, totalling 17,520 variables. So, only 48 variables were considered (four variables times 12 dwellings), and the start time was assumed to be fixed every day.

On the other hand, two managing strategies were designed based on two ideas. The first one was that renewable energy (PV) supplies peak power in the middle of the day. Therefore, the start times of the appliances were set in the central hours of the day using a normal distribution whose average value was the hour with maximum daily irradiance and a deviation, the maximum deviation of the time-scheduling appliances.

The other managing strategy was based on the hourly electricity prices, so the appliances were placed in time in the slots when electricity prices were lower, that is, in valley periods. Fig. 7 shows the distribution of the start times of the appliances for the three cases analysed. Fig. 7a shows the one-year times for the four household appliances over 365 days, distributed according to the maximum irradiance of each day. In Fig. 7b, the distribution is in intervals where prices are lowest during the day. Fig. 7c comprises only 48 times a day for the 12 dwellings, and it is observed that the optimisation is closer to the distribution of prices than the irradiance distribution.

Table 15 shows a summary of the three options for the scheduling of household appliances. The results obtained in the previous sections have been added to this table to provide a complete comparison. In particular, the results of the installation without self-consumption (Tables 7 and 8) and sizing optimisation (Tables 10, 11 and 12) have been added.

From a simple inspection of Table 15, the COE values obtained for the different studies (sizing, sizing plus programming, and sizing plus management using irradiance and energy prices) are very similar. These values present a standard deviation of 0.0073 and 0.0015 in the case of individual self-consumption without and with surpluses, respectively. And 0.0048 and 0.0011 standard deviations for the collective self-consumption, respectively, without and with surpluses. Note that the similarity in self-consumption with surpluses is even more significant. Given these results, a plausible explanation is that household appliances are scheduled within the PV generation window, i.e. during the daytime use period. In these circumstances, the range of solutions is scattered, and the results are similar.

However, an interesting result is produced in managing household appliances using hourly energy prices for self-consumption without surpluses in an individual house. A better COE is obtained for an installation without a battery and PV panel. That is, optimising only the appliances is better than installation with self-consumption.

4.4. Collective sharing of the renewable energy generated

In order to calculate the electricity bill for each household, it is necessary to divide the renewable energy generated by the installation among the different participants. Annex I of Royal Decree 144/2019 [20] establishes the sharing of the net hourly energy generated individually for each participant in collective self-consumption. This energy is shared out through sharing coefficients (β_i). The weight of these coefficients may be any, provided that all the consumers agree and that the summation of the coeffi-

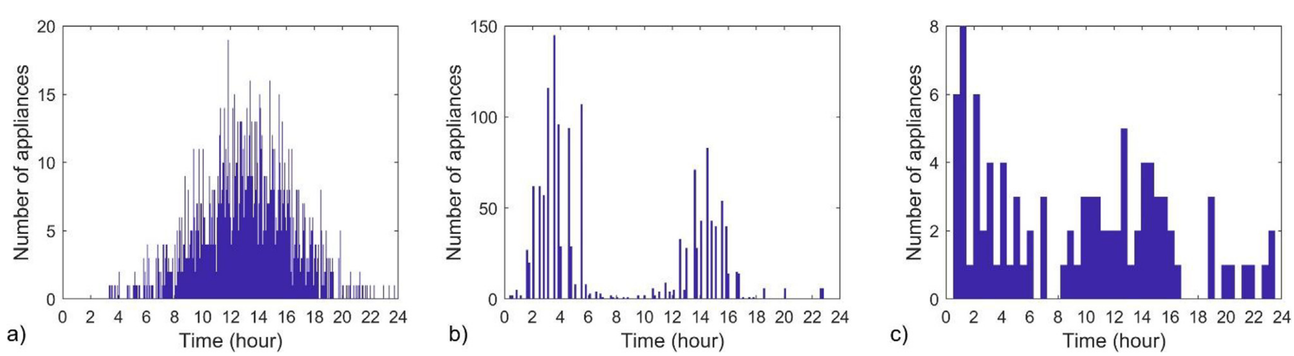

Fig. 7. Appliances start time distribution. a) Irradiance strategy b) PVPC strategy and c) Scheduling optimisation.

Table 15
Total results for individual and collective dwellings (whole year model).

Dwellings	Self-consumption modality	Type of optimisation	Annual bill (€)	NPC (€)	Ann. Cost (€)	Energy (kWh)	COE (€/kWh)	Battery Size (kWh)	PV Size (kWp)
Individual	Without self-consumption	Not applicable	1595.62	19879.37	1595.62	4361.95	0.36580	–	–
	Self-consumption without surplus	Sizing	1172.86	19368.67	1554.63	4361.95	0.35641	0.00	2.08
		Sizing plus Scheduling	1114.88	18458.95	1481.61	4361.95	0.33967	0.00	1.88
		Sizing plus managing (Irrad.)	1142.89	18996.41	1524.75	4360.46	0.34968	0.00	2.08
		Sizing plus managing (Price)	1542.02	19211.59	1542.02	4361.94	0.35352	0.00	0.00
	Self-consumption with surplus under compensation	Sizing	416.13	12023.70	965.08	4361.95	0.22125	0.00	4.39
		Sizing plus Scheduling	414.03	11834.27	949.88	4361.95	0.21776	0.00	4.20
		Sizing plus managing (Irrad.)	416.61	11935.65	958.02	4360.46	0.21971	0.00	4.28
		Sizing plus managing (Price)	411.85	11884.16	953.88	4361.94	0.21868	0.00	4.29
Collective	Without self-consumption	Not applicable	1461.93	18213.79	1461.93	3953.07	0.36982	–	–
	Self-consumption without surplus	Sizing	1079.72	15389.67	1235.26	3953.07	0.31248	0.00	22.53
		Sizing plus Scheduling	1085.13	15405.77	1236.55	3953.07	0.31281	0.00	21.85
		Sizing plus managing (Irrad.)	1050.44	15019.33	1205.53	3952.63	0.30499	0.00	22.46
		Sizing plus managing (Price)	1118.94	15578.72	1250.43	3953.06	0.31632	0.00	18.56
	Self-consumption with surplus under compensation	Sizing	412.86	8816.47	707.66	3953.07	0.17901	0.00	45.56
		Sizing plus Scheduling	406.87	8747.12	702.09	3953.04	0.17761	0.00	45.62
		Sizing plus managing (Irrad.)	413.22	8752.81	702.55	3952.63	0.17774	0.00	44.65
		Sizing plus managing (Price)	408.48	8688.89	697.42	3953.06	0.17642	0.00	44.59

cients is the number of participants. In any case, these coefficients must have fixed values for all the hours of a billing period. The sharing is carried out according to (20), where E_G is the total energy generated by the installation, E_{Gi} is the generated energy assigned to each dwelling, β_i is the sharing coefficient and n is the number of dwellings.

$$E_{Gi} = \frac{\beta_i}{n} E_G \tag{20}$$

In its fifth additional provision, Royal Decree 144/2019 [20] made provision for the subsequent modification of Annex I to implement dynamic distribution coefficients for collective self-consumption. Subsequently, Order TED/1247/2021 [29], amended Royal Decree 144/2019 and incorporated the possibility of using variable distribution coefficients in collective self-consumption. These coefficients must be provided in advance ex-ante and for one year. Regarding the possibility of applying dynamic coefficients ex-post, the Order postponed its application for future analysis to allow gradual progress towards a more dynamic self-consumption. The main difference between ex-ante and ex-post coefficients is the way these coefficients are taken into account to elaborate the electricity bill. Ex-ante means that the sharing coefficients are sent to the commercial company before the billing period, while ex-post means that these coefficients can be sent after the billing period, or calculated dynamically and based on, for instance, the dwelling energy demand.

In this paper, the authors evaluated the study of sharing coefficients for collective self-consumption, first fixed and *ex-ante*, then dynamic *ex-post*. The optimisation comprised the sharing coefficients and using the COE as the objective function. The study used the whole-year model and applied it to the two modalities of self-consumption. Regarding the size of the PV, the sizing optimisation results from Section 4.2 was used. Regarding the calculation of the *ex-ante* sharing coefficients, considering that the consumption of each dwelling predominantly affects the COE, and as this is not known a priori, the *ex-ante* calculation is an unrealistic proposition. Nevertheless, this *ex-ante* information was used as a possible estimate to analyse the solution reached.

Columns 2 and 3 of Table 16 show the results for the two self-consumption modalities, without surpluses and with compensation of the surpluses fed into the grid, respectively. The sharing coefficients obtained in both cases are similar. They are also similar to the distribution coefficients calculated using a distribution proportional to the energy demanded by each dwelling (column 3 of Table 16). Table 17 shows the results corresponding to the cost of energy (COE) in the two self-consumption modalities, considering the flat, optimal and energy-demanded apportionments. These

Table 16
Sharing coefficients.

Sharing	Optimal		Demand
	Without surpluses	With surpluses	
β_1	1.1274	1.1097	1.1131
β_2	0.7756	0.7598	0.7773
β_3	0.8704	0.8739	0.8700
β_4	1.1436	1.1510	1.1320
β_5	0.9301	0.9372	0.9341
β_6	0.8327	0.8451	0.8410
β_7	0.9532	0.9372	0.9547
β_8	0.9783	0.9754	0.9749
β_9	1.1104	1.1085	1.1121
β_{10}	1.0143	1.0304	1.0288
β_{11}	1.1402	1.1287	1.1220
β_{12}	1.1238	1.1432	1.1400

Table 17
COE for different sharing coefficients (€/kWh).

Self-consumption	Sharing		
	Flat	Optimal	Demand
Without surpluses	0.312480	0.312145	0.312147
With surpluses	0.179014	0.177848	0.177849

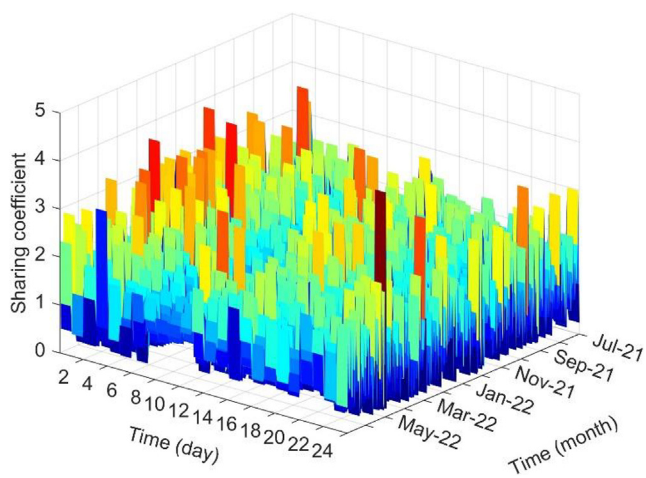

Fig. 8. Hourly sharing coefficients.

results indicate that optimal distribution improves by 0.11 % and 0.65 % for the self-consumption modalities without and with surpluses, respectively. On the other hand, and more importantly, a distribution proportional to the consumption of each dwelling produces results that are very close to the optimum.

Considering these acceptable results obtained by the pro-rata sharing based on the energy demanded, a new analysis of the two self-consumption modalities using a whole-year model was accomplished. In both cases, the energy cost was calculated for one year, obtaining 8760 coefficients for each dwelling. These calculations were performed ex-post, once the hourly consumption of each household was known and in the billing period of one month. The results obtained offer COEs of 0.309394 €/kWh and 0.1777603 €/kWh, reducing 0.98 % and 0.86 % for the modalities without and with surpluses, respectively. Fig. 8 shows the sharing coefficients for the dynamic case (one house). Note that, due to the higher demand variability in a day, these coefficients can reach values from 0 to 3.4.

In view of the results obtained, it would only be advisable to carry out a dynamic hourly sharing according to consumption. Nevertheless, dynamic distribution is not currently permitted by Spanish regulations, as established by Order TED/1247/2021 [29].

5. Conclusions

Currently, in Spain, the situation of high prices in the cost of energy makes the use of self-consumption, both individual and collective, profitable. The two most important conclusions drawn from the study are that a self-consumption installation with surpluses under the simplified compensation mechanism is much more profitable than self-consumption without surpluses. Secondly, a collective installation is more profitable than an individual one, regardless of the type of self-consumption modality.

Regarding the two models used in the paper, it is concluded that the average day model is unsuitable for self-consumption. The evaluation of billing with household loads with different daily patterns and the monthly compensation mechanism causes the results to differ substantially from those obtained by the whole-year model. The results obtained in the case of the average day model overestimate the profitability (COE) and the installation sizing. In the context of sizing optimisation, using a battery for energy storage is not cost-effective in grid-connected systems.

Concerning the scheduling of household appliances, the two online proposed strategies offer similar results to schedule optimisation. In the irradiance-based scheduling, it was foreseeable as the PV generation window is located within the hours of use of the domestic loads. The consumption at the beginning and the end of the day could make the load scheduling during these hours profitable. However, for many months the energy generated is higher than the energy demanded, which mitigates the effect of scheduling the domestic loads. Similar conclusions are achieved when scheduling using the prices. In addition, the results fetched do not support a significant benefit in grid-connected systems with solar PV renewable energy, concluding that scheduling household appliances in self-consumption modalities in grid-connected systems is neither favourable nor promising.

From the results obtained when allocating the total energy generated by the installation among the participants, it can be concluded that an ex-ante allocation is a situation of considerable uncertainty, as there is no prior information to ensure a profit. It is therefore not advisable, unless it is done on a historical basis. If the allocation of sharing were dynamic and ex-post, it can be argued that it could be optimised. However, such a problem would be computationally costly, given the number of variables involved and the economic cost of implementing it, which would be passed on in billing.

Finally, regarding the simplified compensation mechanism established in Royal Decree 144/2019 [20], the authors consider that the regulation might create a mechanism to compensate for the extra energy delivered to the grid in case of a negative monthly energy balance. This excess is more than twice the imported energy. Note that, generally, the demand is higher in winter than in summer; on the contrary, in summer, PV production is more significant than in winter. As the size of the PV system is fixed and optimised for a year, a large amount of energy will be exported in summer and fed back into the distribution system.

Data availability

Data will be made available on request.

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.

References

[1] A. Jager-Waldau, G. Adinolfi, A. Batlle, M. Braun, C. Bucher, A. Detollenaere, K.H. B. Frederiksen, G. Graditi, R.G. Lemus, J. Lindahl, G. Heilscher, M. Kraiczy, G. Masson, B. Mather, C. Mayr, D. Moneta, D. Mugnier, J. Nikoletatos, G. Neubourg, G. Platt, A. Reinders, M.B. Roberts, Y. Ueda, Self-consumption of electricity produced with photovoltaic systems in apartment buildings - Update of the situation in various IEA PVPS countries, Conference Record of the IEEE Photovoltaic Specialists Conference. 2020-June (2020) 0938–0950. 10.1109/PVSC45281.2020.9300442.

[2] C. Gallego-Castillo, M. Heleno, M. Victoria, Self-consumption for energy communities in Spain: A regional analysis under the new legal framework, Energy Policy 150 (2021), https://doi.org/10.1016/j.enpol.2021.112144.

[3] E. Commission, Best practices on Renewable Energy Self-consumption Accompanying, European Commission, Brussels, 2015.

[4] F. Cucchiella, I. D'Adamo, M. Gastaldi, S.C.L. Koh, Renewable energy options for buildings: Performance evaluations of integrated photovoltaic systems, Energ. Buildings 55 (2012) 208–217, https://doi.org/10.1016/j.enbuild.2012.08.029.

[5] D.L. Talavera, J. De La Casa, E. Muñoz-Cerón, G. Almonacid, Grid parity and self-consumption with photovoltaic systems under the present regulatory framework in Spain: The case of the University of Jaén Campus, Renew. Sustain. Energy Rev. 33 (2014) 752–771, https://doi.org/10.1016/j.rser.2014.02.023.

[6] R. Luthander, J. Widén, D. Nilsson, J. Palm, Photovoltaic self-consumption in buildings: A review, Appl. Energy 142 (2015) 80–94, https://doi.org/10.1016/j.apenergy.2014.12.028.

[7] V. Bertsch, J. Geldermann, T. Lühn, What drives the profitability of household PV investments, self-consumption and self-sufficiency?, Appl Energy 204 (2017) 1–15, https://doi.org/10.1016/j.apenergy.2017.06.055.

[8] F.M. Camilo, R. Castro, M.E. Almeida, V.F. Pires, Economic assessment of residential PV systems with self-consumption and storage in Portugal, Sol. Energy 150 (2017) 353–362, https://doi.org/10.1016/j.solener.2017.04.062.

[9] G. Cerino Abdin, M. Noussan, Electricity storage compared to net metering in residential PV applications, J. Clean. Prod. 176 (2018) 175–186, https://doi.org/10.1016/j.jclepro.2017.12.132.

[10] P. Lazzeroni, F. Moretti, F. Stirano, Economic potential of PV for Italian residential end-users, Energy 200 (2020), https://doi.org/10.1016/j.energy.2020.117508.

[11] P. Virtič, R. Kovačič Lukman, A photovoltaic net metering system and its environmental performance: A case study from Slovenia, Journal of Cleaner Production. 212 (2019) 334–342. 10.1016/j.jclepro.2018.12.035.

[12] M.B. Roberts, A. Bruce, I. MacGill, Impact of shared battery energy storage systems on photovoltaic self-consumption and electricity bills in apartment buildings, Appl. Energy 245 (2019) 78–95, https://doi.org/10.1016/j.apenergy.2019.04.001.

[13] C. Avilés A., S. Oliva H., D. Watts, Single-dwelling and community renewable microgrids: Optimal sizing and energy management for new business models, Applied Energy. 254 (2019) 113665. 10.1016/j.apenergy.2019.113665.

[14] D. Frieden, J. Roberts, A.F. Gubina, Overview of emerging regulatory frameworks on collective self-consumption and energy communities in Europe, International Conference on the European Energy Market, EEM. 2019-Septe (2019). 10.1109/EEM.2019.8916222.

[15] I. Campos, G. Pontes Luz, E. Marín González, S. Gährs, S. Hall, L. Holstenkamp, Regulatory challenges and opportunities for collective renewable energy prosumers in the EU, Energy Policy 138 (2020), https://doi.org/10.1016/j.enpol.2019.111212.

[16] J.E. Contreras-Ocana, A. Singh, Y. Besanger, F. Wurtz, Integrated Planning of a Solar/Storage Collective, IEEE Trans. Smart Grid 12 (2021) 215–226, https://doi.org/10.1109/TSG.2020.3020402.

[17] A. Ibarloza, I. Heras-Saizarbitoria, E. Allur, A. Larrea, Regulatory cuts and economic and financial performance of Spanish solar power companies: An empirical review, Renew. Sustain. Energy Rev. 92 (2018) 784–793, https://doi.org/10.1016/j.rser.2018.04.087.

[18] BOE, Real Decreto 900/2015, de 9 de octubre, por el que se regulan las condiciones administrativas, técnicas y económicas de las modalidades de suministro de energía eléctrica con autoconsumo y de producción con autoconsumo., 2015. http://www.boe.es.

[19] BOE, Real Decreto-ley 15/2018, de 5 de octubre, de medidas urgentes para la transición energética y la protección de los consumidores., 2018.

[20] BOE, RD 244/2019, 5 abril, por el que se regulan las condiciones administrativas, técnicas y económicas del autoconsumo de energía eléctrica., 2019.

[21] E. Rosales-Asensio, M. de Simón-Martín, D. Borge-Diez, A. Pérez-Hoyos, A. Comenar Santos, An expert judgement approach to determine measures to remove institutional barriers and economic non-market failures that restrict photovoltaic self-consumption deployment in Spain, Sol. Energy 180 (2019) 307–323, https://doi.org/10.1016/j.solener.2019.01.031.

[22] J. López Prol, K.W. Steininger, Photovoltaic self-consumption regulation in Spain: Profitability analysis and alternative regulation schemes, Energy Policy 108 (2017) 742–754, https://doi.org/10.1016/j.enpol.2017.06.019.

[23] J. de la Hoz, H. Martín, A. Alonso, A. Carolina Luna, J. Matas, J.C. Vasquez, J.M. Guerrero, Regulatory-framework-embedded energy management system for microgrids: The case study of the Spanish self-consumption scheme, Applied Energy. 251 (2019) 113374. 10.1016/j.apenergy.2019.113374.

[24] J. López Prol, K.W. Steininger, Photovoltaic self-consumption is now profitable in Spain: Effects of the new regulation on prosumers' internal rate of return, Energy Policy 146 (2020), https://doi.org/10.1016/j.enpol.2020.111793.

[25] P. Escobar, E. Martínez, J.C. Saenz-Díez, E. Jiménez, J. Blanco, Profitability of self-consumption solar PV system in Spanish households: A perspective based on European regulations, Renew. Energy 160 (2020) 746–755, https://doi.org/10.1016/j.renene.2020.06.135.

[26] J.M. Roldán Fernández, M. Burgos Payán, J.M. Riquelme Santos, Profitability of household photovoltaic self-consumption in Spain, Journal of Cleaner Production. 279 (2021). 10.1016/j.jclepro.2020.123439.

[27] Á.J.O. Mendieta, E.S. Hernández, Analysis of PV self-consumption in educational and office buildings in Spain, Sustainability (Switzerland). 13 (2021) 1–16, https://doi.org/10.3390/su13041662.

[28] G. Jiménez-Castillo, C. Rus-Casas, G.M. Tina, F.J. Muñoz-Rodriguez, Effects of smart meter time resolution when analyzing photovoltaic self-consumption system on a daily and annual basis, Renew. Energy 164 (2021) 889–896, https://doi.org/10.1016/j.renene.2020.09.096.

[29] BOE, Orden TED/1247/2021 de 15 de noviembre, por la que se modifica, para la implementación de coeficientes de reparto variables en autoconsumo colectivo, el anexo I del Real Decreto 244/2019, de 5 de abril, por el que se regulan las condiciones administrativa, 2021.

[30] R.V. Rao, Jaya : A simple and new optimization algorithm for solving constrained and unconstrained optimization problems, Int. J. Ind. Eng. Comput. 7 (2016) 19–34, https://doi.org/10.5267/j.ijiec.2015.8.004.

[31] A.J. Gil Mena, A. Bouakkaz, S. Haddad, Online Load-Scheduling Strategy and Sizing Optimization for a Stand-Alone Hybrid System, J. Energy Eng. 147 (2021) 04020078, https://doi.org/10.1061/(ASCE)EY.1943-7897.0000725.

[32] IDAE, Consumos del Sector Residencial en España. Resumen de Información Básica, (2018) 1–16. https://www.idae.es/uploads/documentos/documentos_Documentacion_Basica_Residencial_Unido_c93da537.pdf.

[33] IDAE, Consumo por usos del sector residencial, (2020). https://informesweb.idae.es/consumo-usos-residencial/.

[34] REE, Usa la energía con cabeza, 2010. https://www.ree.es/sites/default/files/downloadable/guia_consumo_v2.pdf.

[35] REE, ¿Cómo consumimos electricidad?, (n.d.). https://www.ree.es/ sites/default/files/interactivos/como_consumimos_electricidad/preguntas.html.

[36] ESIOS, Active energy invoicing Price, (2022). https://www.esios.ree.es/en/pvpc (accessed October 13, 2022).

[37] European Commission, Photovoltaic Geograplical Information System, (2022). https://re.jrc.ec.europa.eu/pvg_tools/en/ (accessed January 13, 2022).