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Article

Demand-Side Management Method for Households with Self-Generation and Storage of Electricity

Vicente León-Martínez *, Clara Andrada-Monrós, Elisa Peñalvo-López and Juan Ángel Saiz-Jiménez

Department of Electrical Engineering, Universitat Politècnica de València, Camino de Vera 14, 46022 Valencia, Spain; claanmon@etsii.upv.es (C.A.-M.); elpealpe@upvnet.upv.es (E.P.-L.); jasaiz@die.upv.es (J.Á.S.-J.)
* Correspondence: vleon@die.upv.es; Tel.: +34-96-387-95-92

Abstract: The main objective is to propose a calculation method for assessing the benefits of individual domestic prosumers in self-consumption and economic savings when managing their own energy resources. The paper applies the demand-side management concept in the residential sector from the individual domestic perspective so that customers can understand the value of their own sustainable energy resources, conducting self-generation and demand management. The novelty lies in allowing the prosumer to manage their own energy resources to their benefit at a reasonable cost, instead of participating in automated large residential demand-side-management programmes that respond to the means of the grid system operator or other energy service companies, such as aggregators. A methodology for calculating the self-consumption rate and the economic benefit for the consumer is proposed, including three different cases: consumer demand is higher than self-generation, and consumer demand is equal to self-generation, and consumer demand is lower than self-generation. The methodology is validated with actual data from a household in Valencia (Spain) during a complete year, obtaining an average reduction in the annual electricity bill of 70% and a demand coverage with the self-renewable system reaching values of 80% throughout the year. The significance of this methodology goes beyond the economic revenue of the individual consumer; it also aims to guide consumers towards efficient practices in the use of their available energy resources and raise awareness on their energy behaviour.

Keywords: energy transition; active demand-side management; residential load management; renewable energy; load prioritisation

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1. Introduction

According to the current energy model, cities are responsible for 75% of total primary energy consumption and 80% of greenhouse gases [1], mainly due to their concentrated populations, commercial and industrial activities, and transport systems. Urban areas often have a higher density of residential buildings, leading to increased energy consumption for heating, cooling, lighting, and appliances. Based on the Building Stock Observatory of the European Commission [2], there are approximately 196 million buildings within the Member States of the European Union, and most of them are residential [2]. Specifically, the floor area of the residential building stock accounts for approximately 75% of the total, while the remaining 25% is non-residential [2]. Regarding energy consumption, buildings represent 20 to 40% of the global final energy consumption in Europe [3]. In 2022, final energy consumption in European residential buildings represented 21% of the overall building stock, including the categories: Residential, Non-residential, Building construction industry, Other construction industry, and Other [4].

During the last year, the average household electricity prices in Europe were 28.9€ per 100 kWh, including all components in the electricity bill (the cost of electricity, power capacity, distribution, and taxes). The largest increase was in the Netherlands (953.2%), followed by Lithuania (87.8%) and Romania (77.3%) [5]. On other continents like Asia, Africa, or South America, the average cost of electricity is approximately 0.06 €/kWh, 0.1 €/kWh, and 0.11 €/kWh, respectively [6]. However, low electricity prices may represent the use of pollutant fossil fuels, which are very detrimental to the planet in the medium to long term.

These high electricity prices and preoccupations about electricity produced with polluting energy sources have persuaded residential consumers to invest in small renewable home systems for self-consumption and modify their energy consumption patterns, translating loads to low-price periods of time-of-use tariffs.

Assistance to the consumer has been provided through expensive Home Energy Management Systems, which have been introduced in recent years to facilitate automatic energy management in the home, reducing energy demand by shifting load from peak to off-peak hours [7], but requiring major investments. These systems have evolved to disaggregate domestic loads for better management and have integrated new loads existing at the residential level, such as electric vehicles [8]. However, these systems must be integrated into households, whose users must be able to afford the economic and technological resources involved. In this context, it is important to emphasise that the main motivation of individual domestic consumers is to reduce electricity bills by adapting to their own generation profile while maintaining comfort by modifying their energy behaviour and implementing simple demand-side management actions [9]. In this sense, it is important to understand the factors that drive behaviours and encourage actions to be taken to achieve greater efficiency [10]. Studies show that limited knowledge about energy management and the amount of energy used in their household affect motivation to act. Providing residential consumers with comprehensive information on the direct impact their actions have on reducing energy consumption, as well as other indirect actions (such as reducing showering time or using warm water for washing up) results in a reduction of energy consumption [11,12].

The aim of this work is to develop a methodology to empower domestic consumers in managing their own energy resources. The novelty lies in locating the domestic consumer at the centre of the energy transition paradigm [13,14], engaging them in first-hand management of their own energy resources, such as their home renewable generation system, modifying their energy behaviour (demand flexibility), or using a storage system.

It represents a procedure to actively involve domestic consumers in the energy transition for the building sector, minimising the greenhouse emissions, and enhancing the use of renewable energy sources. Alongside, this approach raises energy conservation awareness in society, organically motivating changes in lifestyle with a lower price than automated systems and favouring the energy transition in the residential sector.

2. State-of-the-Art

The origin of Electricity Demand Management dates back to the 1970s in the United States (USA) with the issuance of the Public Utility Regulatory Policies Act (PURPA), which was part of the Energy Policy and Conservation Act [15]. Later, in 1985, Gellings et al. [16] presented Demand-Side-Management (DSM) as the cornerstone of utility planning, implementing a series of demand response actions to influence the time and amount of energy used by customers to achieve desired changes in the utility's system load shape [17–21].

Demand Response (DR) Programmes for utilities [22,23] are classified into price-based demand response and incentives offered:

- Time-based DR programmes are based on offering consumers different tariffs for different time periods. In this context, consumers tend to transfer their manageable loads to periods with a lower price, resulting in a demand reduction at peak hours of the day, benefiting grid management. Consumers actively influence their load usage profile patterns according to the change in tariffs (Real-Rime or Time-of-use), but no direct equipment control occurs [24–27].

- Incentive-based DR programmes. In this programme, DR actions are agreed upon in advance between the consumer and the utility or aggregator. In this agreement, specific customer incentives and conditions for load management are defined (e.g., pre-notice time, energy packages to be managed, duration of the event, etc). DR events may result in load interruption or load translation to more convenient time periods for the grid, which may cause undesirable inconveniences for the final users. Some examples are Direct load control (DLC), interruptible/reduced rates, or Demand bidding programmes [28–30].

Over the past years, numerous research studies have been carried out to analyse the actual and future supply and demand energy patterns in the residential sector [31–36]. Research works focus on the characterisation of the energy profile of households (apartments and single-houses), consumers' preferences, and impact over the grid management [37–39] in order to facilitate utilities´ planning activities while benefitting the consumer with a reduction in their energy bills. These studies are mainly concerned with load shape, peak load, and quality of service provided by power companies [40–47], using Energy Management Systems capable of communicating with the Grid Management Operator to facilitate automated demand response actions. However, benefits for individual prosumers are secondary, not reaching their full potential from the individual prosumer perspective.

A revision of the literature reveals several projects in demand-side management [48–55], mainly focused on the benefits that automated load domestic management can offer the grid management system. Table 1 shows significant projects that have served as the basis for the development of demand-side management in the domestic sector around the globe. However, fewer references enhance the individual benefit of the final prosumer, understanding the economic and energy potential benefits from the user perspective.

Enhancing the economic and energy benefits of the consumer by managing their available energy resources (small domestic renewable energy system for self-supply, battery storage system, load, and grid management potential) is the main objective of this methodology. It evaluates two dispatch strategies: economic and self-consumption. The economic dispatch strategy increases the economic savings for the individual consumer (€) based on the balance between the energy packages bought from the retailer and the excess energy sold to the market, while the self-consumption dispatch strategy focuses on getting the most out of the available renewable generation and storage units, aiming for higher rates of self-consumption.

Both dispatch strategies are assessed in the three possible cases that may occur in an hourly-basis operation of the energy system, depending on the energy needs of the individual consumer and the availability of various energy resources. Case 1 represents the scenario when renewable and battery storage systems supply less than needed by the consumer. Case 2 analyses the situation in which the energy demanded by the consumer is similar to the renewable generation supplied by the system, considering the storage units. Finally, Case 3 corresponds to the scenario in which the renewable and storage systems supply more energy than needed by the consumer, therefore generating an energy surplus.

The work presented in this paper is organised into six sections. The Section 1 is a brief introduction to the current situation regarding consumers in residential buildings, while the Section 2 is devoted to a review of the literature related to energy consumption in residential buildings and the potential of demand-side management for domestic customers. Section 3 describes the method used for calculating the two dispatch strategies (economic and self-consumption) in the three cases. Then, Section 4 presents the results of applying the methodology in a case study located in Valencia (Spain), and Section 5 comments on the results of the case study. Lastly, Section 6 presents the conclusions.

Table 1. Previous projects on demand management in the residential sector.

Active DSM Projects	Country	Description
Energy-Smart Pricing Plan (ESPP) (2004) [56]	EEUU	It studies the response of residential consumers to hourly prices imposed by the electricity market, the type of measures taken by consumers, and the definition of the magnitude of the effect. However, no advice is given to the participants, so the savings achieved can only be visualised after the measures have been implemented.
Newmarket Hydro Time-of-Use Pricing Pilot (2008) [57]	Canada	It aims to provide consumers with information on how to manage electricity consumption by shifting the use of household appliances to off-peak periods. In this pilot, all participants are informed about the cost of energy in each period, a comparison between tariffs according to their historical data, a questionnaire on the use of household appliances, and some tips. It is a very comprehensive pilot that incorporates the use of the Electric Vehicle (EV) for charging as an additional device. However, this pilot does not evaluate the self-consumption of the domestic prosumer and their benefits.
GAD Project: Active Demand Management (2010) [58]	Spain	The aim of this project is to research and develop tools to help reduce consumers' electricity bills, and search for devices that inform the user about the price and origin of the energy. Consumers can adjust their consumption profile according to their preferences, thus reducing their electricity bills. Also, it can be integrated into homes, and considers the need to integrate devices to automate the management and information system. However, it does not address the possibility of introducing renewable energies as a source of generation to optimise the consumption curve, avoiding peaks in the electricity system, nor does it introduce the possibility of obtaining tariff incentives thanks to the use of renewable energies.
FLEXCoop (2021) [59]	FLEXCoop Consortium	This European project adapts demand to production but gives flexibility to consumers by allowing energy savings and using the flexibility margin obtained in the electricity market. It focuses on energy communities, so it considers other actors (Producers, Transmission System Operator, Prosumers, Aggregators, etc.) creating an energy market. This enhances the value of creating methodologies and tools to facilitate active demand management, as they would support the creation of energy communities.

3. Methodology

This section presents the methodology that analyses the benefits of the individual small domestic consumer when managing their own energy resources (self-generation, small battery storage system, load management, and grid), independently from nearby consumers or the grid system requirements. This allows small domestic consumers to better comprehend their energy patterns and generation/storage capabilities, so they can reduce their energy bill while increasing their energy awareness and understanding of the actual energy system.

The methodology involves several input parameters that are essential for performing calculations and providing results in accordance with the domestic user (Figure 1). The calculation method quantifies the revenue of small home customers considering their hourly available energy resources using two dispatch strategies: Economic and Self-consumption. In both cases, the small domestic consumer can buy energy packages from the retailer when necessary and sell the excess energy at the energy market price, in accordance with current Spanish legislation.

The first dispatch strategy focuses on enhancing the economic revenue of the customer, considering that the small consumer can use their own resources and may buy and sell energy packages from the retailer at their convenience. The second dispatch strategy enhances the self-consumption capacity of the small consumer, mitigating the exchange of energy with the grid, which acts as a backup when the small consumer cannot make use of its own generation, storage, and load management resources. The calculation for both dispatch strategies is conducted on an hourly basis during a complete year to assess the small consumer benefits.

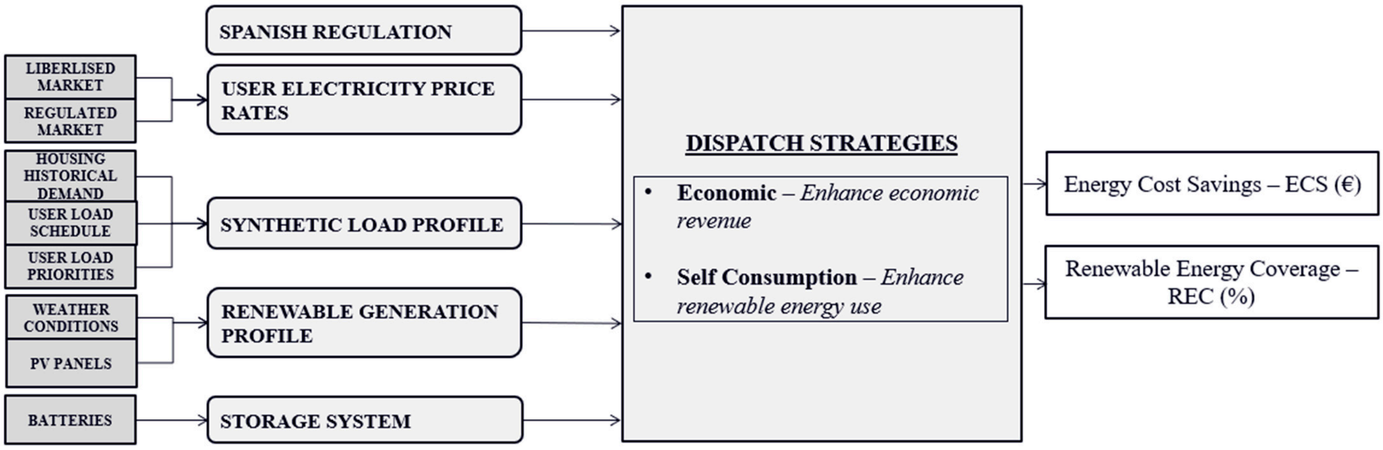

Figure 1. Methodology for energy resource management in small domestic consumers.

This assessment allows grid system operators and other electrical agents, such as aggregators, to compare the benefits obtained by the small domestic customer when managing their own energy resources with the support of the grid, with the benefits offered by utilities for participating in collaborative demand-side management programmes, so competitive and fair rewards for their participation in demand response actions can be offered.

The benefits for the small energy consumer are represented in two main parameters or outputs: Energy Cost Saving (ECS) and Renewable Energy Coverage (REC), calculated for both dispatch strategies to analyse the trade-off between the customer´s final economic revenue and energy independence.

3.1. Input Parameters

Input parameters represent the data and necessary information for executing the calculation method to obtain the desired outputs. Following the rationale in Figure 1, inputs are organized into five modules, which are Spanish regulation, User Electricity Price Rates, Synthetic Load Profile, Renewable Generation Profile, and Storage system. Table 2 indicates the means of data collection for the modules and some sub-modules.

Table 2. Input parameters for the methodology and means of data collection.

Input Parameters	Means of Collection
Spanish regulation	Information gathered from the Spanish national government, Ministry of Ecological Transition, Decree 244/2019 of April 5, which regulates the administrative, technical, and economic conditions of the self-consumption of electrical energy [60]
User Electricity Price Rates	Energy price set by the electricity market (in the case of Spain, the Iberian Energy Market Operator—OMIE) [61]
Housing Historical Demand	Data are collected by the smart metre, owned by the energy distribution company
User Load Schedule	Provided by the user
User Load priorities	Provided by the user
Renewable Generation Profile	Data specifications of the components
Weather conditions	Specifical data of the weather from official webpages
Storage system	Data specifications of the components

- Spanish regulation [60]: Provides information about the policies of the current legislation. At this moment in Spain, the actual self-consumption regulation allows small domestic consumers to adopt a compensation regime, acquiring and delivering energy packages from and to the grid based on the consumer demand needs.
- User Electricity Price Rates: Corresponds to the hourly electricity price paid by the small consumer for consuming electricity at a specific hour of the day. It is obtained from the Spanish System Operator (OMIE) [61], based on the actual energy contract of the consumer (regulated tariff or real-time energy market prices).
- Synthetic Load Profile: Represents the hourly electricity demand of the small domestic consumer. The Synthetic Residential Load Electricity profile is composed of a continuous and a discontinuous load profile. The input parameters are based on historical demand, the consumer's usage preferences associated with their household equipment, the time range of use, and the flexibility of use (whether they are willing to consume the energy package at other times of the day).
- Renewable Generation Profile: This input provides an hourly data vector with 8760-values of the annual electricity generated with the home renewable system. Renewable generation depends on the solar radiation of the location and the characteristics of the photovoltaic solar installation.
    - o Weather Conditions: Temperature and solar radiation parameters are used to calculate the power generator with photovoltaic panels.
    - o Characteristics of the PV installation: Technical specifications of the whole photovoltaic system (number of panels, inverter, wiring, etc.).
- Storage system: Represents the technical characteristics of the battery storage system and main parameters such as the state of charge, depth of charge, and storage capacity.

3.2. Dispatch Strategies

This section presents the two dispatch strategies defined in the methodology, namely Self-consumption and Economic. The self-consumption dispatch strategy focuses on reducing dependency on the grid, consuming the energy surplus generated by the home renewable energy system in secondary loads initially identified by the domestic consumer. The Economic dispatch strategy enhances the revenue of the consumer, transferring low and medium priority loads to less costly time periods and selling the electrical energy surplus into the power market. Both dispatch strategies are simulated in the three possible cases (demand is greater than self-generation, demand is equal to self-generation, and demand is smaller than self-generation) on an hourly basis during a complete year (Table 3).

Table 3. Cases analysed in the hourly calculation method.

Case	Condition	Description
1	Generation $<$ Demand	Value of Renewable Generation in hour *i* is lower than the value of Demand in hour *i*. Instantly, only part of the demand is supplied; therefore, it is analysed whether or not there is energy available in the storage system to supply the demand completely. • Case 1a—Self-Consumption Dispatch Strategy: Actions are taken to disaggregate demand and transfer it to hours with available generation or battery. • Case 1b—Economic Dispatch Strategy: In this case, the consumer carries out a greater effort, including, in addition to the previous actions, the transfer of unsupplied demand to more economical periods.
2	Generation $\approxeq$ Demand	The value of Renewable Generation in hour *i* is equal to the customer´s demand for the hour under study; the demand may be fully satisfied, and there will be no energy surplus.

Table 3. *Cont.*

Case	Condition	Description
3	Generation > Demand	If the value of Renewable Generation in hour *i* is greater than the value for that hour, the consumer's demand can be fully satisfied, and there will be a surplus of energy. • Case 3a—Self-Consumption Dispatch Strategy: The consumer will be able to recharge the batteries, supply secondary consumption to make greater use of the energy generated, and finally, inject surplus energy into the grid. • Case 3b—Economic Dispatch Strategy: In this case, the actions of the previous case are carried out except for supplying secondary consumption. The aim is to inject the surplus completely into the grid.

The different possible cases according to the generation and demand conditions are shown in the following high-level decision-making diagram (Figure 2), which represents the decision path followed by each of the three possible cases. The decision-making path for Case 2 does not imply any action since the demand profile (D0) for that hour matches that of generation; therefore, it is the same for both dispatch strategies. In Case 1 and 3, the decision-making process is different in each dispatch strategy, so it is developed for each dispatch strategy.

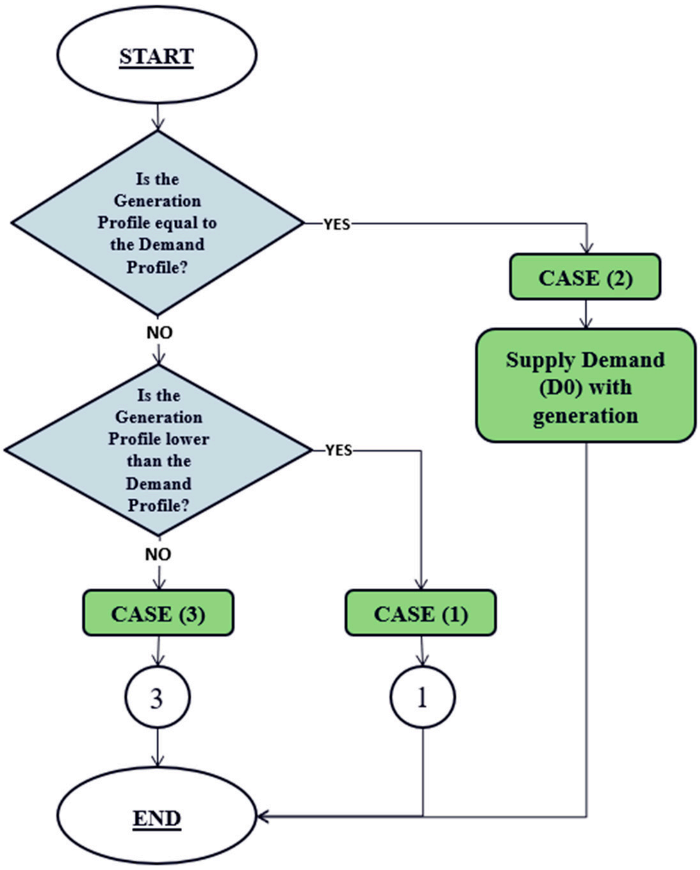

Figure 2. Diagram of the three cases under study.

The decision-making diagrams belonging to the Self-Consumption Dispatch Strategy will be named with the letter "a" (i.e., Case 1a and Case 3a), and those belonging to the Economic Dispatch Strategy with the letter "b" (Case 1b and Case 3b) for ease of understanding.

3.2.1. Self-Consumption Dispatch Strategy

In this strategy, the decision-making process focuses on enhancing self-consumption of the small home renewable system, using an energy storage system to satisfy consumers' peak demand, and supplying energy to secondary loads in case of an energy surplus. It should be noted that the energy resources are variable and depend on the small home renewable equipment (i.e., power of PV panels used, whether batteries are used, etc.), the load priorities set by the domestic consumer, and the number of secondary demand alternatives.

Figure 3 represents the decision-making path for Case 1a in the self-consumption dispatch strategy, for which home renewable generation is less than the consumer demand at a specific hour. As observed in Figure 2 above, if there is a deficit of energy to satisfy the demand, then the energy needed is extracted from the battery storage system, if available, to fulfil the energy requirements of the consumer, according to the diagram in Figure 3. When the energy supplied by the battery storage system is still not enough to satisfy all the demand, it is possible to disaggregate consumption according to the priorities given by the user to make maximum use of the battery. Afterwards, the decision-making process proceeds to transfer low-priority loads to other time-periods according to the user's load schedule preferences. If the energy deficit to satisfy the demand remains after load management, the necessary energy is purchased from the grid.

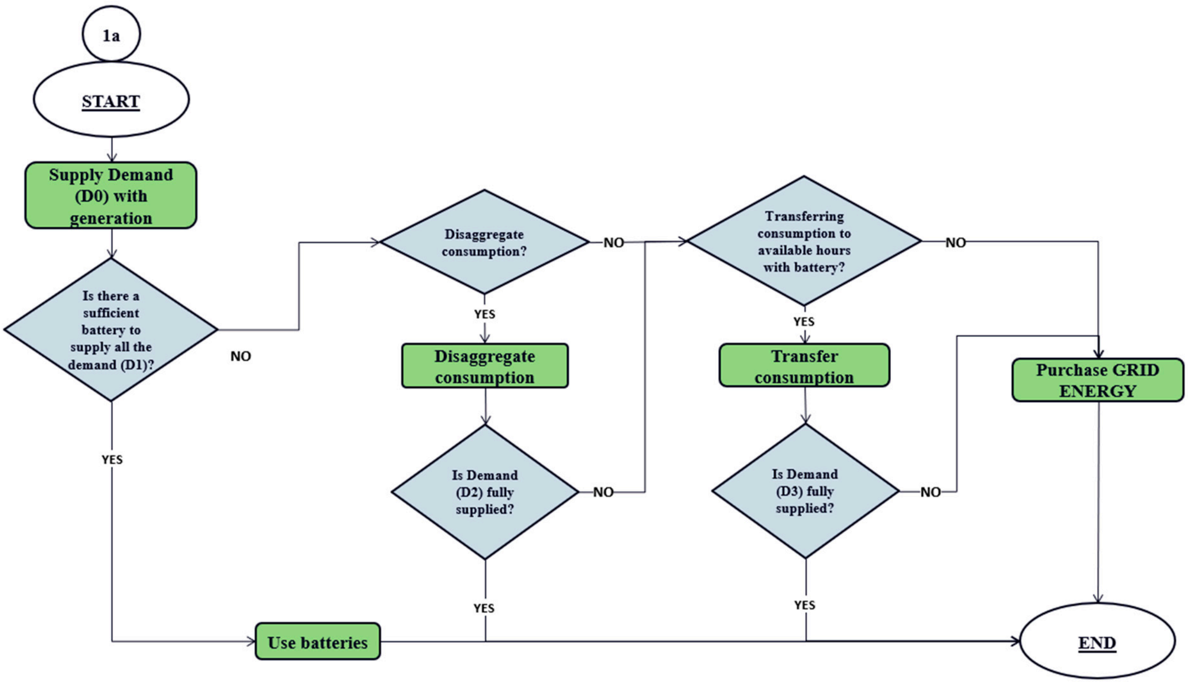

Figure 3. Decision-making diagram for Case 1 in the Self-consumption Dispatch Strategy (a).

Case 3a represents the event in which the energy generation is higher than the energy demand (Figure 4). On this occasion, there is an energy surplus after supplying the energy demand, which is sent to the batteries to be charged. If renewable sources still generate more energy than required by the demand, the secondary consumptions defined by the user are satisfied, and finally, energy is delivered into the grid with economic retribution. Secondary consumption offers greater use of the energy generated, always at the hours when surplus energy is produced. Thus, they allow the user to be more aware of the use and management of their generated energy, naming this dispatch strategy as self-consumption.

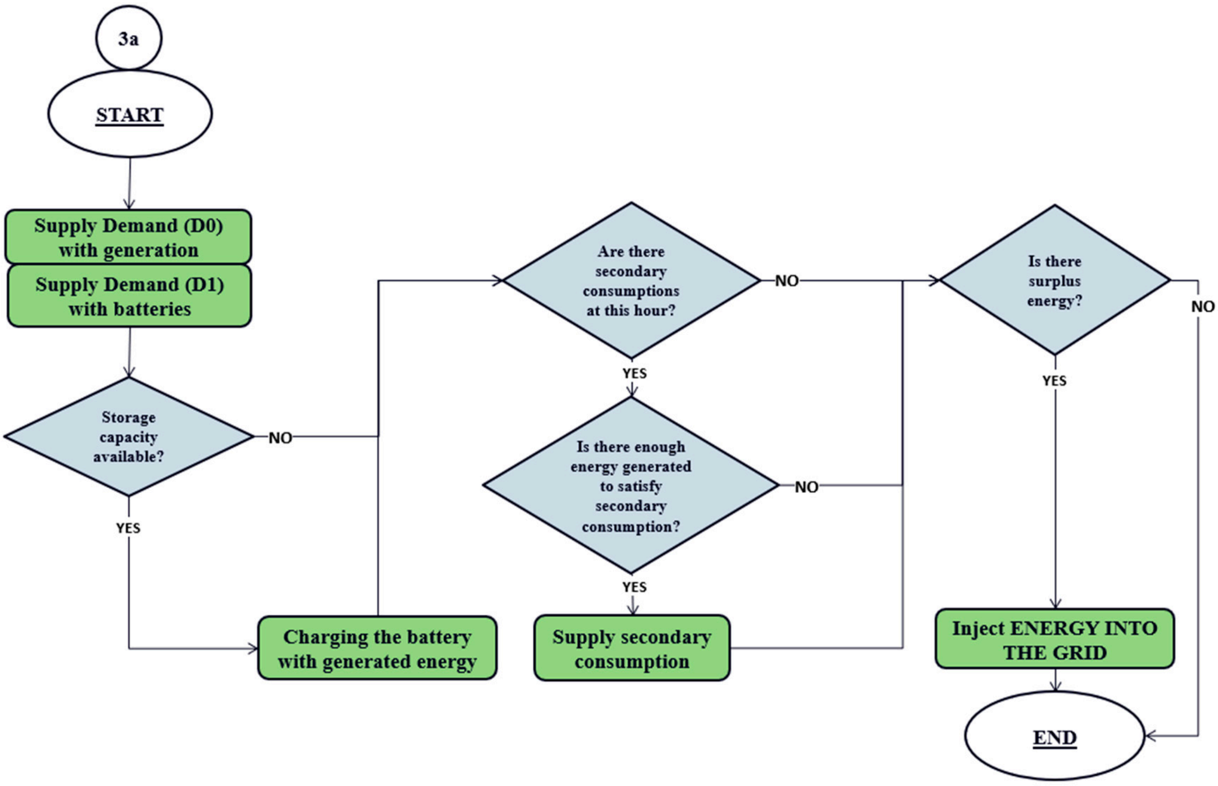

Figure 4. Decision-making diagram for Case 3 in the Self-consumption Dispatch Strategy (a).

3.2.2. Economic Dispatch Strategy

The Economic Strategy also considers the home renewable energy system for self-supply in conjunction with the battery storage system. The main difference from the previous self-consumption strategy is that it prioritises the management of low and medium priority loads during lower-priced timeslots, then, delivers the excess of energy to the grid to obtain economic retribution of the energy sold, instead of satisfying secondary demands of the consumer.

The specific decision-making process for Case 1b, as shown in Figure 5, represents the case in which renewable energy generation is lower than the consumer´s demand. In this event, the demand that is not satisfied by the home renewable energy system is supplied by the battery storage system in the first instance, and if this is not possible, by disaggregating consumption according to the priorities given by the user. In case additional energy is needed to satisfy the demand, loads are shifted to available battery hours (given by the user), and if the demand is fully satisfied, loads are shifted to other time periods with lower prices. In the occasion that further energy is required to satisfy the demand, the remaining energy is purchased from the grid.

Finally, the decision-making diagram for Case 3b of the Economic Dispatch Strategy is provided in Figure 6, corresponding to the case when home renewable generation is higher than the customer's demand for a given hour. In this situation, after satisfying the consumer´s energy demand, the energy surplus is stored in the battery storage system. If the batteries are fully charged, the excess of energy is delivered to the grid with corresponding economic compensation.

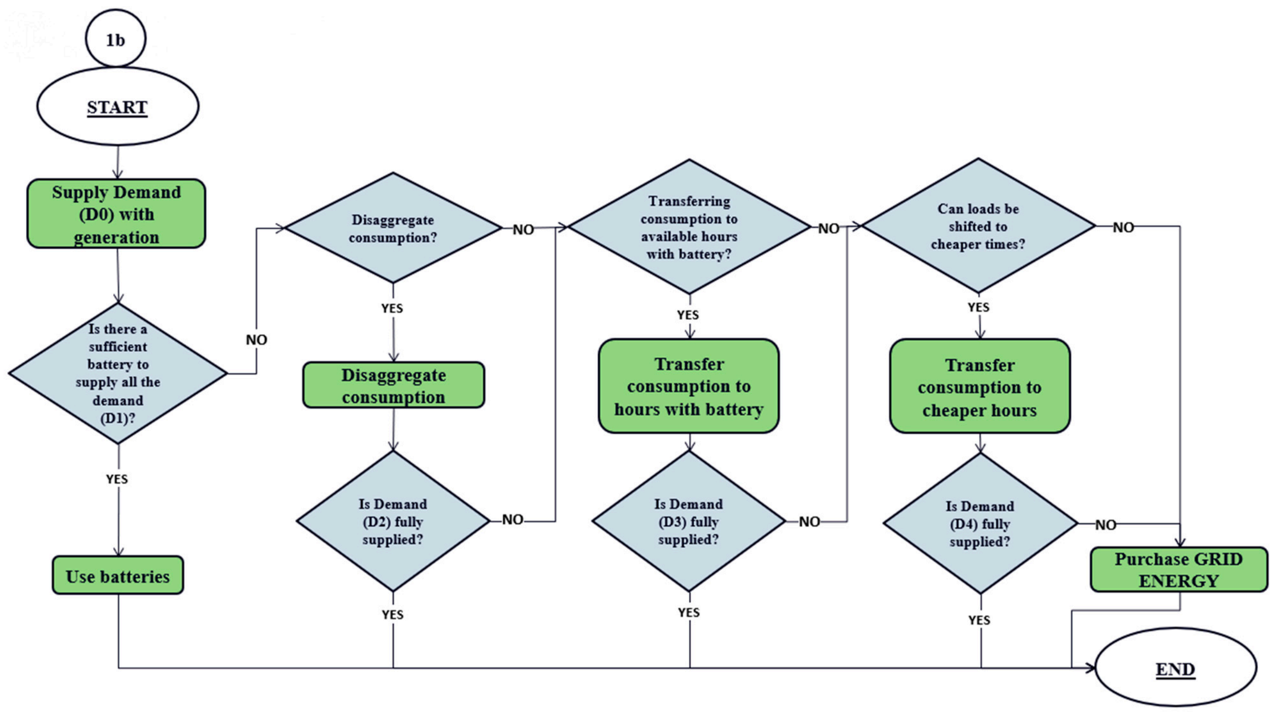

Figure 5. Decision-making diagram for Case 1 in the Economic Dispatch Strategy (b).

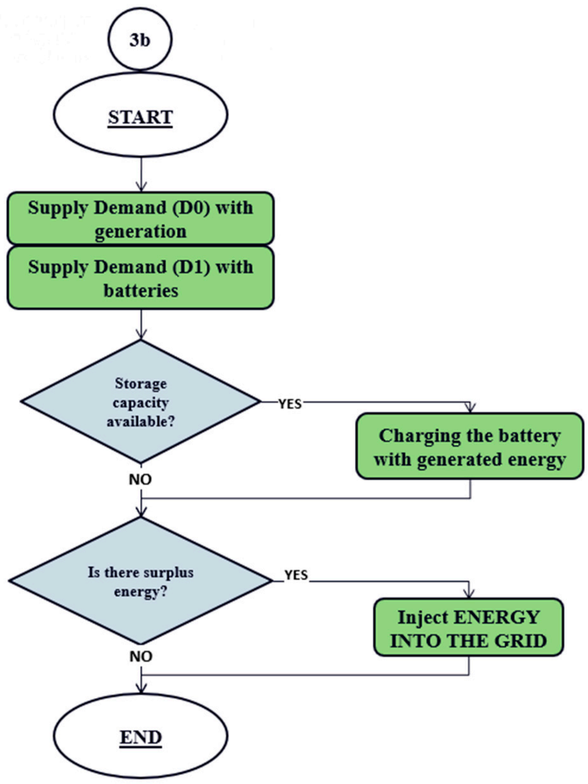

Figure 6. Decision-making diagram for Case 3 in the Economic Dispatch Strategy (b).

3.3. Output Parameters

The output parameters are defined to compare the results in both dispatch strategies (self-consumption and economic) to evaluate the degree of energy independence achieved by the consumer and the consumer´s economic revenue when conducting load management actions to low price timeslots. These would be the main parameters to be provided to the consumers to understand the results of their actions, following the trend of other papers [26,28,29,54,55]. In addition, several complementary parameters have also been defined to provide additional information to the consumer, as can be seen in Table 4.

Table 4. Output parameters for the methodology and units.

Output Parameters	Units
Energy Cost Savings—ECS	€
Renewable Energy Coverage—REC	%
Cost of the total electricity purchased—C_f	€
Revenue of the total electricity sold to the market—$E_{d_i}P_{s_i}$	€
Total electricity purchased from the grid—E_{fc_i}	kWh
Total electricity delivered to the grid—E_{d_i}	kWh

The main two parameters are:

- Energy Cost Savings—ECS (€): Cost savings in the electrical energy purchased from the grid. It compares the cost of purchasing all the customer´s energy needs from the grid with the energy purchased from the grid when the prosumer manages their energy resources, including the home renewable energy system, battery storage system, and load management resource.
- Renewable Energy Coverage—REC (%): It represents the degree of energy independency of the customer from the grid. It represents the energy coverage of the customer's electricity demand with the energy produced by the renewable energy.

Other complementary parameters include:

- Cost of the total electricity purchased C_f, (€)
- Revenue of the total electricity sold to the market $E_{d_i}P_{s_i}$ (€)
- Total electricity purchased from the grid E_{fc_i} (kWh)
- Total electricity delivered to the grid E_{d_i} (kWh)

3.4. Output Calculation Methods

3.4.1. Calculation of Energy Cost Savings (ECS)

Equation (1) defines the calculation of the economic savings parameter (ECS) as the difference between the cost of the energy initially consumed C_0 and the cost of the energy finally consumed C_f after applying the methodology. Equation (1) is divided into Equations (2)–(6) for ease of understanding.

$$ECS\ (€) = C_0 - C_f \tag{1}$$

The calculation of the cost of the energy initially demanded between hour i and the defined period t is made in Equation (2) as the Synthetic Load Profile E_{SLP} for each hour i multiplied by the energy price P_{e_i} set by the market or the trader in hour i. This is the energy demand calculated based on the previous demand historical data without applying the methodology proposed in this paper. The formulation of this parameter is further explained in Equation (12).

$$C_o(€) = \sum_{i}^{t} E_{SLP_i} \cdot P_{e_i} \qquad \forall\, i\ \in [0,\ t] \tag{2}$$

The final costs C_f of the final energy consumed in a period t from hour i after applying the methodology are calculated as the difference between the final energy consumed from the grid E_{fc_i} in each hour i times the energy price P_{e_i} for hour i, minus the surplus energy E_{d_i} that has been injected into the grid in hour i times the price P_{s_i} at which the surplus energy is paid in each hour i. This is presented in Equation (3), the terms of which are found broken down in Equations (4)–(6).

$$C_f\ (€) = \sum_i^t \Big[\big[E_{fc_i} P_{e_i} \big] - \big[E_{d_i} P_{s_i} \big] \Big] \qquad \forall\, i\ \in [0,\ t] \tag{3}$$

Regarding the final energy consumed E_{fc_i} after applying the methodology, it is calculated in Equation (4) as the balance established between Synthetic Load Profile E_{SLP} for each hour i, minus the energy self-consumed E_{sc_i} in that hour. The self-consumed energy term E_{sc_i} is broken down in Equation (5) as the sum of the energy produced from the solar panels E_{pv_i} and that coming from the battery E_{bat_i}.

$$E_{fc_i}(\text{kWh}) = E_{SLP_i} - E_{sc_i} \tag{4}$$

$$E_{sc_i}\ (\text{kWh}) = E_{pv_i} + E_{bat_i} \tag{5}$$

Load transfer conditions:

- They are moved to times set by the consumer when the battery is available.
- In the Economic Dispatch Strategy, the condition that they are transferred to the most economical hour (in the off-peak period) is added.

Finally, the energy delivered to the grid E_{d_i} is calculated in Equation (6) and will be the difference between the energy generated and not consumed by the PV panels $E_{g_{pv_i}}$ in hour i, and the sum of the PV energy consumed E_{pv_i}, the battery energy consumed E_{bat_i}, and, in the case of the Self-Consumption Dispatch Strategy, the energy consumed by the secondary consumptions E_{2con_i}.

$$E_{d_i}\ (\text{kWh}) = E_{g_{pv_i}} - E_{pv_i} - E_{bat_i} - E_{2con_i} \tag{6}$$

3.4.2. Calculation of Renewable Energy Coverage (REC)

The coverage of the renewable energy used to supply demand (REC) is calculated in Equation (7) as the summation in a period t for each hour i of the total self-consumed demand D_{sc_i} over the total demand supplied D_{tot_i} during that period t. In this indicator, energy should be considered from the consumer's point of view, i.e., as the energy that the consumer is demanding to cover the necessary loads in that hour.

$$REC(\%) = \sum_i^t \frac{D_{sc_i}}{D_{tot_i}} \cdot 100 \qquad \forall\, i\ \in [0,\ t] \tag{7}$$

The self-consumed demand D_{sc_i} in each hour i will be the sum of the demand supplied by the energy provided by the PV panels E_{pv_i}, by the batteries E_{bat_i}, and by the energy consumed by secondary consumption E_{2con_i}, as represented in Equation (8).

$$D_{sc_i}(\text{kWh}) = E_{pv_i} + E_{bat_i} + E_{2con_i} \tag{8}$$

Initially, Equation (9) defines the terms that compose the total demand D_{tot_i} for an instant I after applying the methodology. The total demand D_{tot_i} for an hour i is calculated as the final demand consumed D_{f_i} and the demand contributed to the grid E_{d_i}. The final demand consumed D_{f_i} is the sum of the energy consumed from the grid D_{fc_i}, the self-consumed demand D_{sc_i}, and the demand transferred D_{trans_i} from other periods to this instant i, as shown in Equation (10). Regarding the transferred appliances D_{trans_i}, according to Equation (11), they will be considered positive when they enter at hour i and negative when they cannot be supplied at hour i and enter at another cheaper hour specified by the user.

$$D_{tot_i}(\text{kWh}) = D_{f_i} + E_{d_i} \tag{9}$$

$$D_{f_i}\ (\text{kWh}) = D_{fc_i} + D_{sc_i} + D_{trans_i} \tag{10}$$

$$D_{trans_i}\ (\text{kWh}) = D_{t-i\ i} - D_{t-o\ i} \tag{11}$$

As mentioned, the secondary consumptions only apply to the self-consumption dispatch strategy. It is used whenever, after having supplied all the demand and transferred loads, there is surplus energy. In this case, those consumptions that the user has considered as secondary can be supplied with the energy surplus for that hour.

3.4.3. Supplementary Terms

Firstly, the method for calculating the Synthetic Load Profile $E_{SLP_{Ci}}$ is defined, which is made up of a continuous $E_{SLP_{Ci}}$ and a discontinuous profile $E_{SLP_{Di}}$.

$$E_{SLP_i}(\text{kWh}) = E_{SLP_{Ci}} + E_{SLP_{Di}} \tag{12}$$

On the one hand, the continuous load profile is a stochastic model that is created from a load profile based on historical demand E_{hd_i} and certain random synthetic perturbation α. The random synthetic perturbation is composed of two terms: the daily perturbation α_{d} and the instantaneous perturbation α_{I}. The daily perturbation maintains the same profile but scales up or down according to maximum variability, while the instantaneous perturbation changes the shape of the load profile according to an assigned variability, but without affecting its size. Equation (13) defines the synthetic random perturbation.

$$\alpha = 1 + \alpha_{\text{d}} + \alpha_I \tag{13}$$

In this paper, the model used randomly draws the value of the daily perturbation once a day from a normal distribution with a mean of zero and a standard deviation equal to the daily variability input, and randomly takes the value of the instantaneous perturbation from a normal distribution with a mean of zero and a standard deviation equal to the instantaneous variability input value. Thus, the continuous synthetic load profile is formed from the historical demand E_{hd_i} multiplied by the synthetic perturbation α_i, as shown in Equation (14).

$$E_{SLP_{Ci}}(\text{kWh}) = E_{hd_i}(\text{kWh}) \cdot \alpha_i = E_{hd_i}(1 + \alpha_{\text{d}} + \alpha_I) \tag{14}$$

On the other hand, the discontinuous load profile refers to the mobile loads entered per user that depend on the day and the conditions given by the generation profile (Equation (15)). This load profile considers the user's load schedule and load priorities. The user appliances schedule consists of data associated with the time of use of the appliances and the flexibility for their use, providing other time slots in which the appliances can be used. In the user load priorities, the consumer provides data associated with the priorities in the interruption and transferability of loads of household equipment based on three levels of priority: high, medium, and low. High priority means that these loads cannot be transferred to other time slots, while low priority is considered as loads that can be used in some other time slot defined by the user in the User Load Scheduling. Finally, the load transfer term E_{t_i} is calculated as in Equation (11) as the balance between the loads entering E_{t-i_i} for hour i and the loads leaving E_{t-o_i} because they cannot be supplied in that hour.

$$E_{SLP_{D_i}}(\text{kWh}) = \sum E_{j_{trans,i}} \tag{15}$$

The solar energy produced by the panels $E_{g_{pv_i}}$ for this model is calculated according to Equation (16), considering the irradiation Gh for the area in which the house is located, being proportional to the area S of the panels and the efficiency Ef of the PV modules.

$$E_{g_{pv_i}}(\text{kWh}) = \frac{Gh\left[\frac{\text{Wh}}{\text{m}^2}\right] \cdot S\ \left(\text{m}^2\right) \cdot Ef\ (\%)}{1000} \tag{16}$$

Another important term is the State of Charge (SoC) of the battery at each hour i. This term depends on the type of installation, since it does not operate in a similar way if it is a home without self-consumption, with self-consumption without surpluses, or with surpluses. In the case of self-consumption without surplus, the PV modules must not generate energy that cannot be stored by the batteries. However, the equations presented enable the calculation of the state of the battery considering the most complicated case, for a self-consumption installation with surplus compensation. The initial state of the battery E_{ibat} for an hour i will depend on the final state of the battery for the previous hour $E_{fbat_{i-1}}$ and the so-called demand D_o. This demand is the difference between the energy generated by the modules $E_{g_{pv_i}}$ and the historical demand E_{fd_i} for that hour.

$$E_{ibat_i} = E_{fbat_{i-1}} + E_{g_{pv_i}} - E_{SDP_i} = E_{fbat_{i-1}} + D_o \tag{17}$$

The State of Charge (SoC) of the battery is defined in Equations (18) and (19). To determine it, firstly it is checked if the state of charge of the battery for the previous hour plus Demand D_o is higher than the maximum battery E_{bat_max}, which refers to the total capacity of the battery in terms of energy. If the upper limit is exceeded, the battery will adopt the maximum battery value, and the surplus will be used according to the methodology. On the contrary, if the limit is not exceeded, it will proceed according to Equation (19).

$$SoC \begin{cases} E_{bat\_max}, & E_{fbat_{i-1}} + D_o > E_{bat\_max} \\ & E_{fbat_{i-1}} + D_o < E_{bat\_max} \end{cases} \tag{18}$$

The Depth of Discharge (DoD) term appears in Equation (19), which indicates the maximum value of the usable capacity of the battery so that its performance is not impaired. Therefore, the battery will adopt the minimum energy value E_{bat_min} in case the difference between the previous final state of the battery $E_{fbat_{i-1}}$ and the Demand D_o is less than the DoD. Therefore, this will be considered when supplying demand D_1.

$$SoC \begin{cases} E_{fbat_{i-1}} - D_o, & E_{fbat_{i-1}} + D_o > DoD \\ E_{bat\_min}, & E_{fbat_{i-1}} + D_o < DoD \end{cases} \tag{19}$$

Finally, it is important to define the priority dispatch strategy used in the batteries for the rest of the demand (other than D_o). The final state of the battery E_{fbat_i} (kWh) for each hour i depends on the use of different strategies to disaggregate consumption, transfer it to the most economical hour, or use it for secondary consumption. Therefore, the final energy of the battery E_{fbat_i} depends on the initial energy available E_{ibat_i}, and the energy remaining after disaggregating $Bat_{dg_{i,j}}$ and transferring $Bat_{lt_{i,j}}$.

$$E_{fbat_i} = E_{ibat_i} - Bat_{dg_{i,j}} - Bat_{lt_{i,j}} \tag{20}$$

The disaggregate and load transfer terms found in Equation (18) are described below:

- Disaggregate (Bat_{dg_i}): This strategy is common to both Dispatch Strategies (self-consumption and economic). It states that if it is not possible to supply all the demand for an hour i, the battery will supply those devices j in order according to the priority k given by the user, until the maximum available battery is used.

$$Bat_{dg_{i,j}}(i,\ j,\ k) \qquad \forall\, j\ \in i \cap k$$

- Load transfer (Bat_{lt_i}): This action is also applicable to both Dispatch Strategies and is implemented after the disaggregation one. If devices have not been supplied due to lack of battery power, they can be moved to hours when battery power is available. This is conducted based on the user´s load priorities.

$$Bat_{lt_{i,j}}\left(i,\ j,\ k,\ E_{fbat}\right) \qquad \forall\, j\ \in i \cap k \cap E_{fbat}$$

3.5. Case Study

To evaluate the methodology, an application case is carried out in a single-family house with self-consumption and batteries for energy storage located in a municipality of Valencia (Spain). The study analyses the use of different energy resources available in the home to benefit the individual consumer with and without the battery storage system.

The house has PV modules on the roof to generate electricity, as well as a lead-acid battery storage system. The installation was designed with a battery storage system, whose maximum capacity is 150 Ah at a voltage of 12 V. The equipment found in the house is a lead-acid battery with a depth of charge of 40% to extend its useful life. The study analyses the benefits of managing the energy resources in the house for self-consumption and economic revenue of the individual prosumer. According to its location (Valencia, Spain), the annual values of solar energy generation with the annual energy demand of the house are shown in Figure 7.

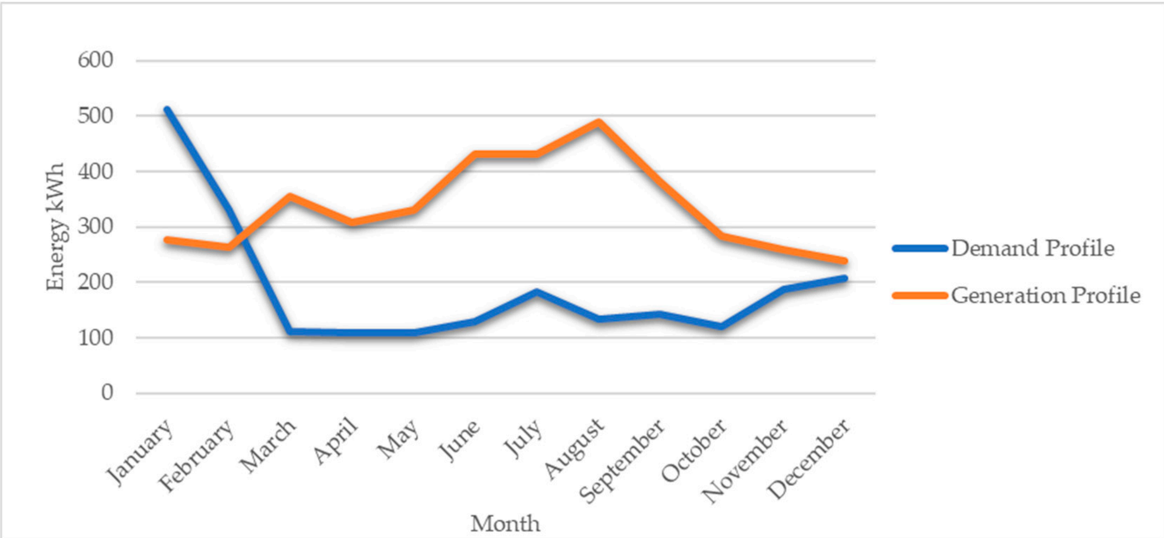

Figure 7. Annual PV Panels generation and household energy demand.

In addition to the information on available energy resources, the consumer establishes their consumption priorities for main home equipment, introducing the hours of use of the appliances and the flexibility range of their use, allowing load management (e.g., shifting consumption from peak to valley).

Figure 8 shows the devices for which the methodology will be applied, the times of use throughout each day, the priorities assigned to each device (high, medium, and low) and the possibility of transferring them to other slots. This table is created for each typical day, and in this case study, summer and winter working days and bank holidays have been established. In addition, secondary devices considered by the user are also included. In this case, they are those intended to activate watering and pool cleaning devices, as they are not strictly necessary, but if they can be used, they will still have a good use and, in addition, will provide greater coverage of the energy generated.

Another input value for the implementation of the methodology is the price of the energy term in addition to the price of the surplus energy that is injected into the grid. Figure 9 provides the values taken in this case study, obtained for the year of study from the Iberian Energy Market Operator.

Devices	Power (kW)	Timetable		Timetable 2		Timetable 3		Time of use (h)	Priority		Interruptibility	Transfer?	Timetable for transferring	
		From	To	From	To	From	To						From	To
Fridge	0.6	0	24					1	1	High	No	No		
Ceramic hob	2.2	14	15	21	22			1	2	High	No	No		
Electric oven	1.8	14	15					1	3	High	No	No		
Washing machine	1	19	20					1	4	Medium	Yes	Yes	16	17
Electric heater	4	7	8	20	21			0.5	5	Medium	Yes	Yes	18	19
Dryer	1.3	21	22					1	6	Medium	No	No		
Iron	1.1	22	23					1	7	Medium	Yes	Yes	7	8
Dishwasher	1.1	15	16					1	8	Medium	Yes	No		
Laptop computer	0.015	20	22					1	9	Low	Yes	Yes	22	23
Television	0.15	15	17	21	24			1	10	Low	Yes	Yes	14	15
Music equipment	0.8	20	21					1	11	Low	Yes	Yes	16	17
Microwave	1.3	8	9	14	15	21	22	1	12	Low	Yes	Yes	22	23

Secondary consumptions									Self-consumption strategy
Devices	Power (kW)	Timetable		Timetable 2		Timetable 3		Time of use (h)	ON/OFF operation
		From	To	From	To	From	To		
Irrigation pump	1	5	7	20	21			1	ON
Purification pump	1	15	17					1	ON
Cleaners	1	1	2					1	ON

Figure 8. Data entered by the user and load priorities.

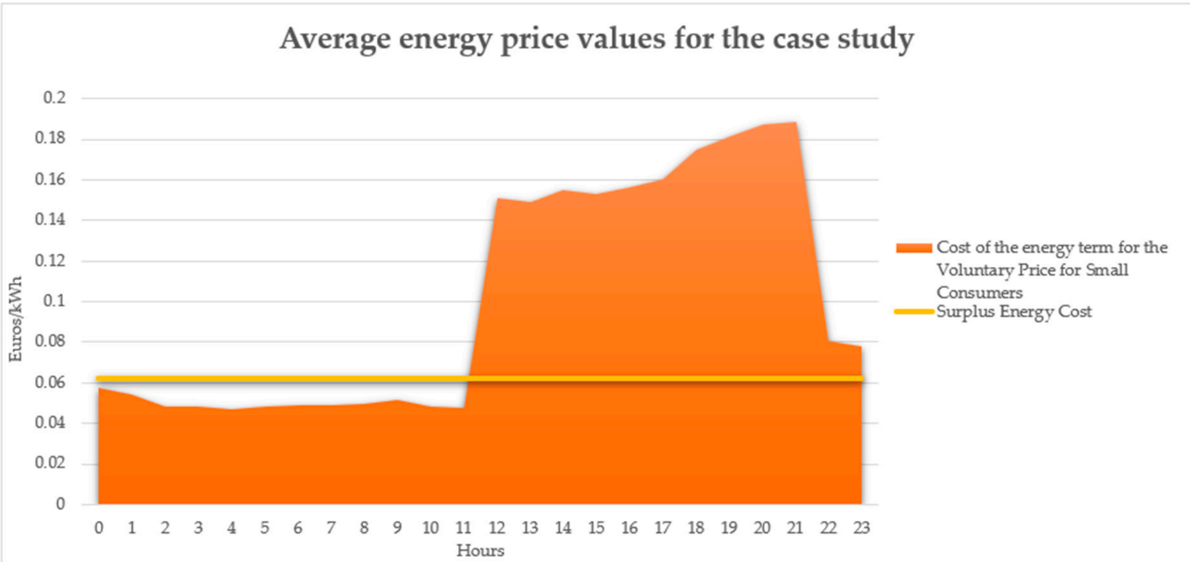

Figure 9. Average energy prices for the case study according to the Energy Market Operator.

Details of the energy resources are summarised in Table 5:

Table 5. Case study: specific input parameters.

Input Parameter	Case Study Data
Type of installation	Self-consumption with surpluses with compensation. Contracted power: P1 = 5.5 kW P2 = 5.5 kW
Tariff group	2.0TD for small consumers
Electrical Market prices	Iberian Energy Market Operator—OMIE
Synthetic Load Profile (SLP)	To define the synthetic load profile, a synthetic perturbation α of up to 1.35 has been considered. The daily α_d and instantaneous α_I perturbation values have been randomly assigned with a maximum value of 20% and 15%, respectively, according to historical residential demand.

Table 5. *Cont.*

Input Parameter	Case Study Data
Generation Profile (PG)	Photovoltaic installation: Peak Power: 1.8 kWp, Efficiency 18%. S = 10 m^2
Weather conditions	Irradiance history for location (39.537–0.632)
Storage Technologies	Maximum capacity: 150 Ah Depth of discharge: 40%
User preferences	Number of available devices, power, weekly hours of use for working days and holidays, usage priorities (high, medium, and low), and flexibility of use for shifting to other times entered by the user.

To illustrate the input data provided and its evolution after applying the methodology, the following figures provide, for a summer working day (Figure 10) and for a winter holiday (Figure 11), the initial and final demand, the battery status, and the energy generation with the solar panels throughout the day.

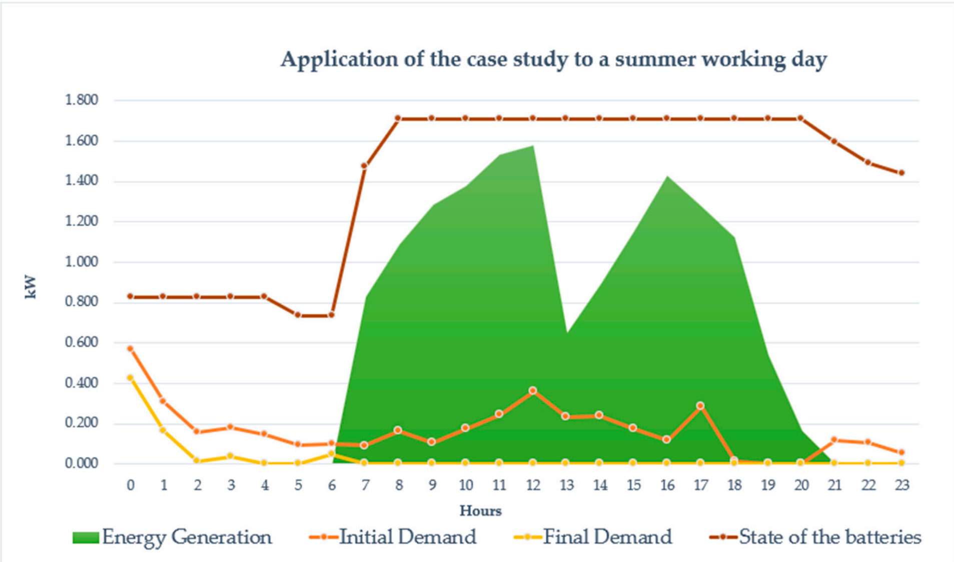

Figure 10. Case study for a summer working day.

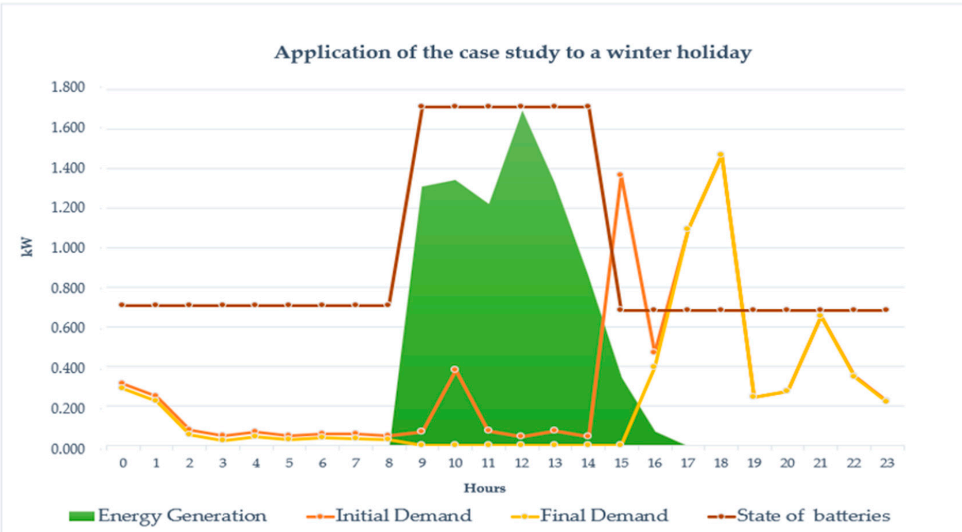

Figure 11. Case study for a winter holiday.

4. Results

The results obtained after applying the methodology in a single house in Valencia (Spain) are shown below. The results are presented with and without batteries for both dispatch strategies. This is intended to provide information on the benefits of applying the two dispatch strategies and the versatility that different energy resources provide for satisfying the demand.

Calculations have been made on an annual basis for each of the outputs defined in the methodology, and monthly graphs have also been provided for the two main outputs: ECS and REC, i.e., economic cost savings and renewable energy coverage of demand. The month selected was July, as it is a summer month with favourable weather conditions for the study of the methodology.

4.1. Case Study without Batteries

This section provides the results of implementing the methodology without the use of battery energy storage. The methodology with the self-consumption and economic dispatch strategies is applied. In this case, it is important to note that since energy cannot be stored in batteries, it is instantaneously used or delivered into the grid.

First, the annual results are shown to illustrate the scope of the methodology. For this purpose, the following table shows the annual values for each of the outputs defined in Section 3.3.

- Energy Cost Savings (ECS) (€): Average economic savings of about 20€ per month are achieved. The economic dispatch strategy presents slightly higher economic savings than self-consumption since it prioritises the transferability of loads to cheaper hours and the sale of energy excess.
- Renewable Energy Coverage (REC) (%): The annual percentage of demand covered by renewable energies is higher than 30% for both criteria, but slightly higher for the self-consumption dispatch strategy since, by introducing secondary consumption, the demand supplied with generation is higher.
- Cost of the total electricity purchased (€): The total energy purchase is about 18€ per month on average, a little higher in the self-consumption strategy because the loads are not shifted to more economical periods.
- Revenue of the total electricity sold to the market (€): This term refers to revenues obtained from the sale of energy. For the economic dispatch strategy, the revenue is equivalent to about 15€ per month. It is slightly lower for the self-consumption strategy. The main difference between the two strategies is that the economic strategy injects all the surplus into the grid, while the self-consumption strategy previously supplies secondary consumption.
- Total electricity purchased from the grid (kWh): This term is provided in terms of energy to be aware of the energy consumed. As can be seen, for both strategies, it is the same value because the demand supplied in terms of energy with respect to the base demand is the same (does not consider secondary consumption).
- Total electricity delivered to the grid (kWh). The energy injected into the grid is superior for the economic strategy since the surplus is not used to supply secondary consumption.

The monthly results obtained in July for the ECS and REC outputs are presented in Figures 12 and 13 below. Monthly results are calculated as the summatory of each hourly electricity value per day of the month represented.

On the one hand, Figure 12 shows that the values of the economic dispatch strategy are higher in terms of energy cost savings (ECS). The use of strategies, such as shifting to more economical periods or grid feeding, is key in this strategy. For this month, a maximum daily saving of up to 1.40€ is obtained.

On the other hand, Figure 13 shows that the demand coverage values for renewables in the self-consumption dispatch strategy are higher or equal to those of the economic dispatch strategy. This is the objective of the self-consumption strategy, to supply a greater part of the demand and use a higher percentage of renewable generation. Specifically, for day 8, demand coverage with renewables is more than 75%.

In relation to day 8, the economic savings are not remarkably high even though the energy used to cover the demand was one of the highest of the month. This is because energy generation was very limited (e.g., cloudy day), so almost all generated energy was used, but no great economic savings were achieved. Another interesting case could be the 29th, where almost 50% of the energy generated is used, and the savings obtained are the highest of the month. Therefore, on this day, it can be said that the energy generated was conveniently managed to cover the demand, as the saving reached a value of 1.40€.

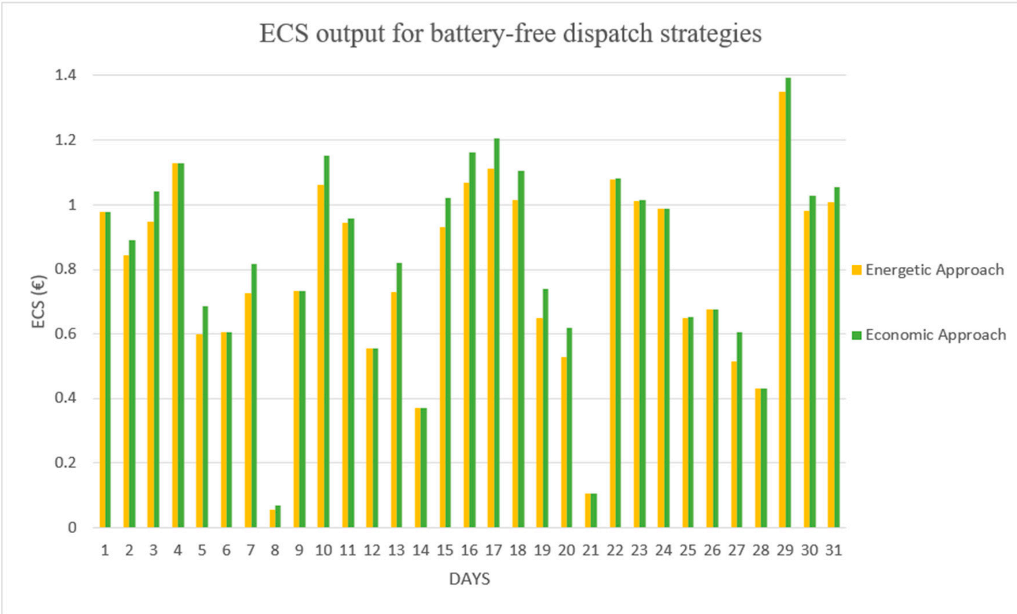

Figure 12. ECS Output (economic savings) for the Self-Consumption and Economic Dispatch Strategies in a summer month for the case without batteries.

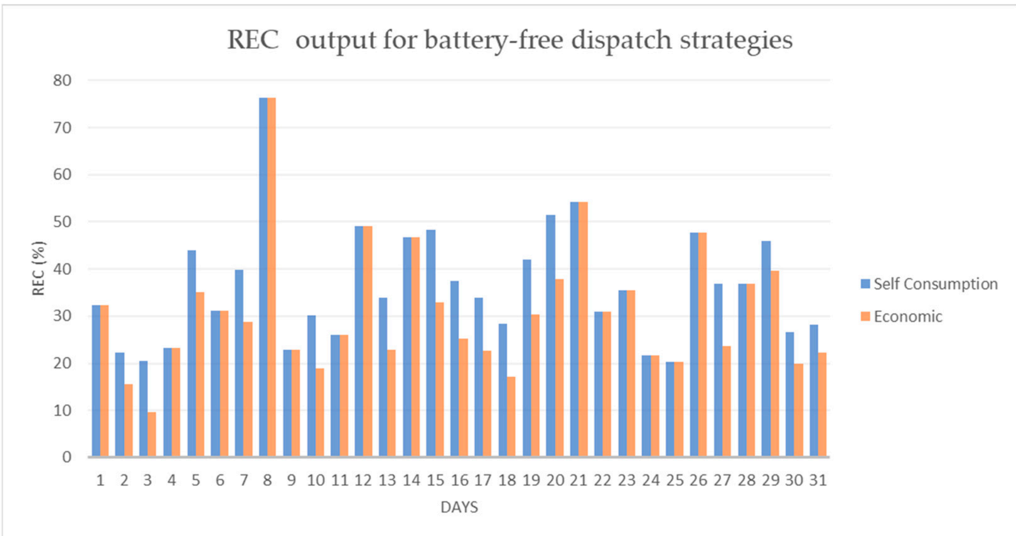

Figure 13. REC Output (use of renewable energy generated) for the Self Consumption and Economic Dispatch Strategies in a summer month for the case without batteries.

In annual terms, the energy generated to supply demand in the case without batteries reaches a value of 36.9% for the energy dispatch strategy and 31.8% for the economic dispatch strategy. Furthermore, this represents savings in energy purchases of 42.65% and 45.02%, respectively.

4.2. Case Study with Batteries

This section provides the results of the case study with the use of batteries for energy storage. As in the case without batteries, annual data are provided for each of the outputs defined in the methodology, as well as monthly graphs of the main outputs. Both cases are compared to analyse the versatility of the battery.

- Energy Cost Savings (ECS) (€): In this case, economic savings are equivalent to about 24€ per month on average, i.e., about 4€ per month more than in the case without a battery. As in the previous case, higher values are obtained in the economic dispatch strategy than in the self-consumption dispatch strategy.
- Renewable Energy Coverage (REC) (%): The coverage of renewable energy over demand is 35% for both criteria, but as in the case of batteries, it is slightly higher in the self-consumption dispatch strategy.
- Cost of the total electricity purchased (€): In the case of batteries, the average monthly energy purchase is about 11€ on average for the self-consumption dispatch strategy and slightly less for the economic one.
- Revenue of the total electricity sold to the market (€): For the economic dispatch strategy, the revenue is equivalent to about 14€ on average per month, and it is slightly lower than the self-consumption strategy.
- Total electricity purchased from the grid (kWh): Demand that must be purchased because it is not supplied by renewable sources. This is identical to the case without batteries.
- Total electricity delivered to the grid (kWh): The energy injected into the grid is superior for the economic strategy, since the surplus is not used to supply secondary consumption.

Finally, Figures 14 and 15 below show the graphs of the ESC and REC outputs for each of the economic dispatch and self-consumption strategies. These graphs have been obtained for a typical summer month, July, to compare the differences between the two strategies with batteries.

Regarding the ESC output, i.e., financial savings, Figure 14 shows cost energy savings on most days of the month. These savings are slightly higher in the economic dispatch strategy, reaching a monthly difference of up to 1.30€. In this case with batteries, the maximum saving obtained is 1.60€ on the 29th, which is 20cts€ more than in the case without batteries.

In the case of the REC output (percentage of renewable energy used), Figure 15 shows higher values for the self-consumption dispatch strategy compared to the economic one for most of the month. However, there are days in which the values are identical because only the measures (load shifting, disaggregate, etc.) common to both dispatch strategies have been used. In this case, energy is managed more equitably throughout the month, obtaining values of up to 63% of demand coverage with the energy generated. These values are higher than in the case of Figure 13 as the use of batteries allows the energy generated to be more flexible. However, for example, on day 8, where in the case without batteries almost all the energy generated was used, in this case, the percentage used is lower. This is because the battery allows deferred demand to be covered, so perhaps energy from the batteries was used to cover the demand, and the rest of the surplus energy could be injected into the grid, thus increasing the savings in the cost of energy for that day.

Therefore, the use of batteries allows flexibility in the use of the energy generated without the need to inject it into the grid, so the REC output is higher, but the correct management of the energy resources also allows the savings in the cost of energy to be higher (by unbundling loads or transferring them to lower-cost periods).

Finally, in annual terms for the case with batteries, the energy generated to supply demand reaches a value of 57.1% for the energy dispatch strategy and 49.7% for the economic dispatch strategy, with the remaining energy fed into the grid. Furthermore, this means savings in energy purchases of 73.40% and 74.40%, respectively, reaching values of over 70%.

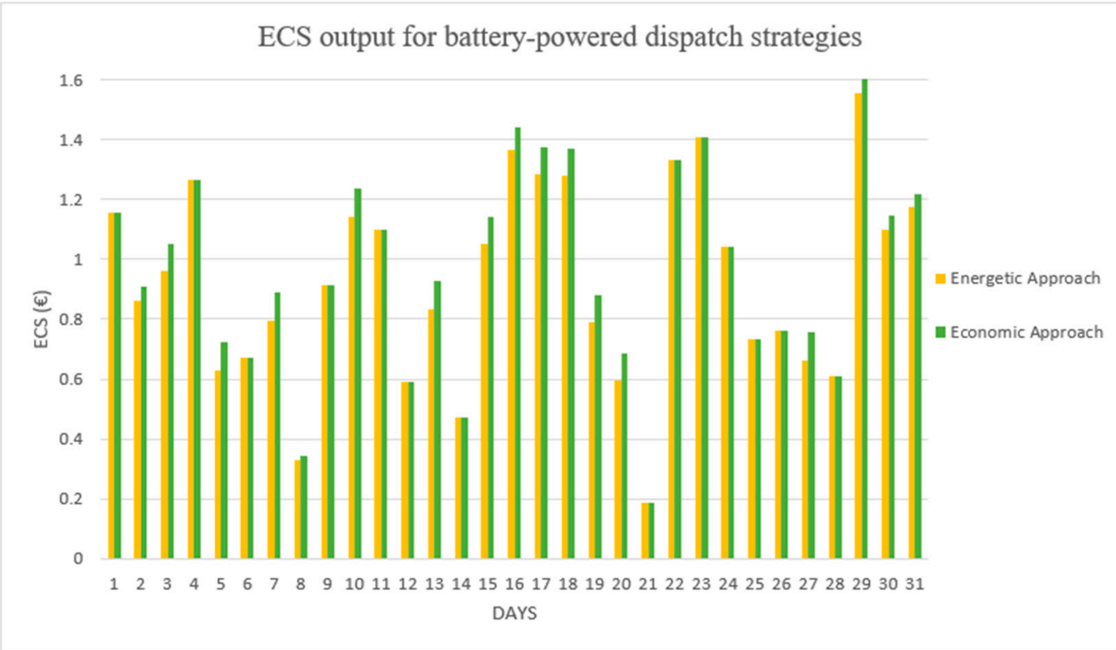

Figure 14. ECS Output (economic savings) for the Self-Consumption and Economic Dispatch Strategies in a summer month for the case with batteries.

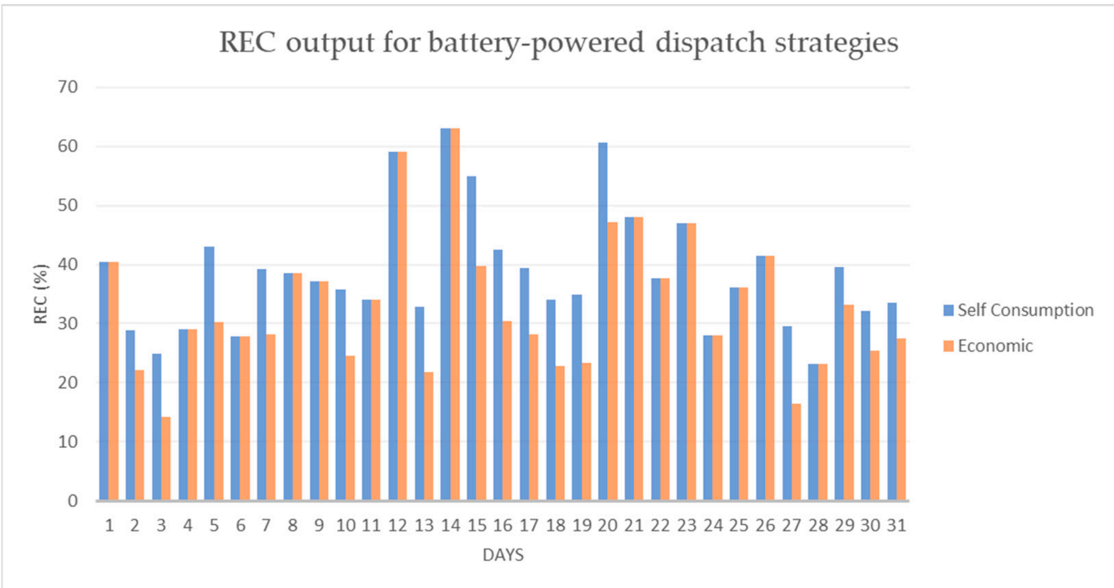

Figure 15. REC Output (use of renewable energy generated) for the Self Consumption and Economic Dispatch Strategies in a summer month for the case with batteries.

5. Discussion

Results of the case study show that the methodology allows for achieving a bill reduction of 70% in comparison to the household´s annual electricity purchased from the grid, by managing all domestic energy resources (generation with photovoltaics, storage system, and demand flexibility). Considering no active participation of the consumer, the electrical bill reduction associated only with self-consumption from the photovoltaic panels reaches a 27% share due to the generation-demand hourly decoupling, while the combination of photovoltaics and battery systems achieves 56% savings in the electrical bill, which includes not only the demand coverage but also selling of the excess of energy into the grid.

Furthermore, the annual results obtained for each of the study cases are analysed: without the use of batteries (Table 6) and with batteries (Table 7) for energy management.

Table 6. Annual output values for battery-free dispatch strategies.

	Economic	**Self-Consumption**
Energy Cost Savings (ECS) (€)	246.59	233.90
Renewable Energy Coverage (REC) (%)	30.89	36.27
Cost of the total electricity purchased (€)	215.85	218.29
Revenue of the total electricity sold to the market (€)	182.21	169.64
Total electricity purchased from the grid (kWh)	1042.44	1042.44
Total electricity delivered to the grid (kWh)	2603.08	2429.25

Table 7. Annual output values for battery powered dispatch strategies.

	Economic	**Self-Consumption**
Energy Cost Savings (ECS) (€)	287.40	275.12
Renewable Energy Coverage (REC) (%)	34.15	39.65
Cost of the total electricity purchased (€)	129.41	130.34
Revenue of the total electricity sold to the market (€)	169.65	143.08
Total electricity purchased from the grid (kWh)	467.20	467.20
Total electricity delivered to the grid (kWh)	2421.76	2044.76

Regarding the ECS output or the economic savings obtained, it is noted that the study case with batteries obtains a slightly higher saving compared to the case without batteries, which corresponds to about 4€ per month on average. This saving represents the reduction of energy purchased from the grid, firstly due to greater coverage of the demand with renewable energy (REC output), and secondly because it is possible to manage the loads better and transfer them to other cheaper periods set by the domestic consumer. It can be said that without the use of batteries, the energy generated through the PV panels must be used directly, so the system loses versatility.

The use of batteries allows flexibility in the generation produced by the PV panels to be consumed later when there is no generation. Therefore, it also conditions the REC output, since a higher percentage of the demand can be covered by the energy from the renewable source stored in batteries. In other words, and according to the data provided, 36% of the demand is covered by renewable energies in the case without batteries, and up to almost 40% in the study case with batteries. So, without the use of batteries, all unconsumed energy is delivered into the grid, as there is no other method of dissipating the energy.

Surplus energy in both study cases is also used to supply secondary consumption in the self-consumption dispatch strategy, so that the energy delivered into the grid is less than in the economic dispatch strategy (2.6 kWh in the economic strategy, while in the self-consumption strategy, 2.4 kWh). Thus, according to the economic dispatch strategy, less energy is consumed from the renewable source (REC Output), and the difference is injected into the grid with the consequent economic retribution. This means that the values for the energy delivered to the grid are even more significant in the study case without batteries, and therefore, the revenue from selling energy to the grid is also higher (182.21€ in the economic strategy for the case study without battery versus 169.65€ in the same strategy for the case with batteries).

In the case without batteries the revenue obtained by selling energy to the grid is higher than in the case with batteries, but also, the cost of the energy purchased is higher. In fact, the balance between purchasing and selling energy to the grid in the case without batteries is positive, i.e., the consumer must buy more energy compared to what the consumer sells. However, the balance for the case with batteries is negative, i.e., the consumer can sell more energy than consumes, so this shows that energy management is better with batteries.

On the other hand, the results reported monthly for the two main outputs (ECS and REC) are also the subject of discussion. The monthly values obtained for the ECS output as an indication of daily savings are higher on daily basis in the case study with batteries (Figure 14) than in the case study without batteries (Figure 12). In fact, the maximum daily savings value achieved is 1.6€, while in the case without batteries, it is 1.4€. However, it can be observed that the use of batteries does not affect each of the strategies separately, i.e., the economic and energy dispatch strategy behave similarly, but the values obtained for the case with batteries are proportionally higher. The same applies to the REC output for the case without batteries (Figure 13) and with batteries (Figure 15). Both dispatch strategies (self-consumption and economic) maintain the same behaviour, but the values are higher on average. That is to say, the percentage of demand covered is higher in the case of batteries than in the case of no batteries.

6. Conclusions

In this research work, savings have been obtained in terms of energy consumption from the grid, as well as for the electricity bill. The methodology allows economic savings on electricity bills, greater energy efficiency, and a consequent reduction in pollutant emissions. Considering the active participation of the consumer managing their demand flexibility resources with and without batteries, the methodology allows an average coverage of the demand with renewable energies from 30% (case study without batteries) to almost 40% (case study with batteries) and reaches values of up to 80% in the case with batteries. In addition, it helps to achieve a significant reduction in the annual electricity bill: up to 246,59€ in the case "without batteries" and up to 287,40€ in the case "with batteries", corresponding to a reduction in electricity bills of up to 70% annually. Furthermore, the case study supports that the use of batteries gives versatility to the proposed methodology, increasing the values of savings and renewable coverage obtained for both strategies. Finally, although it is not contemplated within the methodology, managing the use of energy by delivering the surplus into the grid leaves the door open to its subsequent use in what could be a shared self-consumption. This, together with the possibility of integrating the tool into a home using smart grids, creates expectations for the future in which it could be used through an application as a measure for active demand management in the residential sector.

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Abbreviations

Acronyms	
USA	United States
PURPA	Public Utility Regulatory Policies Act
DSM	Demand Side Management
DR	Demand Response
DLC	Direct Load Control
ESPP	Energy-Smart Pricing Plan
EV	Electric Vehicle
OMIE	Iberian Energy Market Operator
E_{fc_i}	Final energy consumed in each hour i after applying the methodology (kWh)
E_{sc_i}	Self-consumed energy from the renewable source in each hour i after applying the methodology (kWh)
E_{d_i}	Energy delivered from the renewable source to the grid in each hour i after applying the methodology (kWh)
E_{pv_i}	Energy from the PV panels in each hour i after applying the methodology (kWh)
D_{sc_i}	Self-consumed demand in each hour i after applying the methodology (kWh)
D_{tot_i}	Total demand consumed in each hour i after applying the methodology (kWh)
D_{f_i}	Final demand consumed in each hour i after applying the methodology (kWh)
D_{trans_i}	Demand transferred in hour i after application of the methodology (kWh)
E_{SLP_i}	Synthetic profile of the demand initially created to apply the methodology (kWh)
E_{SLPC_i}	Continuous synthetic load profile created from the user's demand history (kWh)
$E_{g_{pv_i}}$	Total energy generated by the PV panels in each hour i (kWh)
E_{ibat_i}	Initial energy of the battery at hour i before applying the methodology (kWh)
E_{fbat_i}	Final energy of the battery at hour i after applying the methodology (kWh)
Variables	
P_{e_i}	Energy price set by the market or the trader in hour i (€/kWh)
P_{s_i}	Surplus energy price set by the market or the trader in hour i (€/kWh)
D_{fc_i}	Demand supplied from the power grid in hour i (kWh)
Symbols	
α	Synthetic perturbation for synthetic load profile modeling.
S	Area covered by the PV Panels (m^2)
α_d	Daily perturbation
α_I	Instantaneous perturbation
t	Hour of the year (complete year includes the 8760 h).

ECS	Energy Cost Savings indicator
REC	Renewable Energy Coverage indicator
PV	Photovoltaic
SLP	Synthetic Load Profile (kWh)
SoC	State of Charge (%)
DoD	Depth of Discharge (%)
Equations	
ECS	Economic costs saved after applying the methodology (€)
REC	Demand covered with renewable energy over total demand supplied (%)
E_{bat_i}	Energy consumed from the battery in hour i (kWh)
E_{2con_i}	Energy consumed by the secondary consumptions in hour i (kWh)
C_0	Cost of the energy initially consumed (€)
C_f	Cost of the energy finally consumed (€)
$D_{t-i\ i}$	Demand transferred from another hour and entered in hour i (kWh)
$D_{t-o\ i}$	Demand leaving hour i and transferred to another hour (kWh)
$E_{j_{trans,i}}$	Historical demand transferred at hour i due to j user-defined devices (kWh)
Gh	Solar irradiation in the corresponding area $\left(\frac{\mathbf{Wh}}{\mathbf{m^2}}\right)$
E_{bat_min}	Minimum battery capacity (kWh)
$Bat_{dg_{i,j}}$	Battery capacity used to supply j equipment transferred at hour i (kWh)
$Bat_{lt_{i,j}}$	Battery capacity used to supply j equipment transferred at hour i (kWh)
Parameters	
D_o	Demand 0 calculated as the difference between the real generation and the historical demand (kWh)
E_{bat_max}	Maximum battery capacity (kWh)
E_{bat_min}	Minimum battery capacity (kWh)
$Bat_{dg_{i,j}}$	Battery capacity used to supply j equipment transferred at hour i (kWh)
$Bat_{lt_{i,j}}$	Battery capacity used to supply j equipment transferred at hour i (kWh)
i	Time variable that includes the 24 h of a day
j	Number of user-defined electrical loads
k	Load transfer priorities according to low, medium, or high.
$\forall$	Universal quantifier meaning "for all".

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