Advantages of Minimizing Energy Exchange Instead of Energy Cost in Prosumer Microgrids

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Abstract: Microgrids of prosumers are a trendy approach within the smart grid concept, as a way to increase distributed renewable energy penetration within power systems in an efficient and sustainable way. Single prosumer individual management has been previously discussed in literature, usually based on economic profit optimization. In this paper, two novel approaches are proposed: firstly, a different objective function, relative to the mismatch between generated and demanded power, is tested and compared to classical objective function based on energy price, by means of a genetic algorithm method; secondly, this optimization procedure is applied to batteries' coordinated scheduling of all the prosumers composing a community, instead of single one, which better matches the microgrid concept. These approaches are tested on a microgrid with two household prosumers, in the context of Spanish regulation for self-consumption. Results show noticeably better performance of mismatch objective function and coordinated schedule, in terms of self-consumption and self-sufficiency rates, power and energy interchanges with the main grid, battery degradation and even economic benefits.

Keywords: distributed energy resources; electric energy storage; energy management system; genetic algorithm; microgrid; prosumer; self-consumption

1. Introduction

Within a context of reinforcing consumers' roles in the energy system and improving energy efficiency in Europe [1], the concept of prosumer has become common in the power system context. A prosumer is a consumer with the ability of producing electric energy to be either self-consumed or injected into the grid. A group of prosumers connected and coordinated to manage their energy resources are considered to be a microgrid [2]. The microgrid can be either isolated or grid-connected, in which energy management and economic profitability are the main targets.

Many studies can be found in literature analyzing microgrids' financial feasibility and the correct sizing of their respective Distributed Energy Resources (DERs) [3,4]. In most of the published works the main objective of the microgrid energy management system is to achieve the highest possible economic benefit by minimizing its operational costs [5,6]. Generation costs [6] and market prices, for the purchased/sold energy [5], are used to define optimization techniques' objective functions. However, economic incentives and additional costs have a great importance in the microgrids' financial

sustainability and they must be considered in their design and operation [3]. Incentives are due to advantages of self-consumption improvement, that lie on empowering consumers by means of their participation in energy management programs, encouraging smarter consumption patterns, reducing peak demand and energy costs, decreasing transmission losses, due to the local generation and consumption, and contributing to finance energy transition [7].

Household prosumers usually count on locally available renewable energy generation, which, in most cases, is enabled by photovoltaic (PV) systems located at the dwellings [8]. In many countries, the decreasing cost of PV system devices has led to a grid-parity in self-generated PV energy in comparison to energy purchased from the grid. In this context, self-consumption achieves economic sustainability, even without financial support from governments.

Under deregulated electricity markets, extended all over Europe, general costs of power systems for building and operating infrastructures are covered by network tariffs and taxes. Network tariffs can be composed by two possible components: volumetric tariffs, according to which consumers pay per unit of purchased energy (€/kWh); and capacity tariffs, applied to the power capacity contracted with the energy provider (€/kW). In both cases tariffs can be classified as flat type, variable with consumption or capacity level and time-of-use type (different tariffs in peak/off-peak hours) [7]. Higher volumetric tariffs motivate for demand reduction, by means of energy efficiency and self-consumption. On the other hand, predominant capacity tariffs lead to peak-shaving.

Regarding energy prices, they are based on a spot market where a clearing price is obtained by the point at which the supply and demand curves meet, according to the European algorithm EUPHEMIA [9]. This market price establishes both purchase and sale prices for consumers and producers, respectively. In addition, the undeniable interest to increase the penetration of energy conversion systems based on renewable primary energy resources and the related motivation to improve self-consumption ratios has led to several promotion policies in different countries. An interesting classification of common incentives to introduce renewable energy resources can be found in [10]. According to this work, promotion policies can be focused on investment or on energy generation, but the most common type of policies in Europe are related to feed-in tariffs (FIT). There are two types of FIT systems: fixed and premium [7,10]. The first one is independent on the electricity market price, facilitating the assumption of investment risks, whereas the second one is an overprice above market price, with the advantage of being attached to the market behavior and thus avoiding excessive remuneration for producers and market distortion [7].

In the case of surplus energy fed into the grid, from prosumers using renewable energy resources, there is not a common understanding in the different European countries about the promotion policies. While many countries support investment or establish FIT frameworks, others prefer net metering approaches. Under this concept, the electricity excess injected into the grid can be later used during higher consumption hours, when self-generated energy is not sufficient [7]. Therefore, the main grid acts as a backup or a virtual storage system to manage the prosumers' energy surplus/deficit. Since energy price may be different during the hours of the day, and it is not considered in net-metering framework, this approach is commonly not favorable from the power system point of view and it is limited to small-size systems. As a consequence, some countries apply the so-called net-billing, which calculates the value of the energy fed into the grid at wholesale price to be used as a credit to purchase energy at other time period [7]. A survey of policies in European countries can be found in [7], although some of them have experienced variations during the last years.

Promotion policies make sense while immature technologies are trying to be introduced or while their marginal costs, when compared to conventional generation systems, do not allow them to participate in a competition market with equal conditions. The natural trend for any promotion policy is to converge into a market approach when grid-parity has been reached.

The case of Spain has been singular both in renewable energy, mainly PV, and in self-consumption promotion policies. The installation of renewable technologies and, especially, PV plants, was strongly boosted from 2007 to 2012, under high incentives in the form of fixed and premium FIT. In 2012

a high so-called "tariff-deficit" was reached which led to the extinction of support schemes for new plants and to changes in remuneration for existing plants, causing financial issues to many investors [11]. PV power plants were primarily promoted during the former years 2007 and 2008 which led to an extraordinary proliferation of this kind of generation systems and improved the experience and background of Spanish renewable energy companies all over the world. Since 2012, new PV power plants can only compete for extra economic support under a capacity-based aid to recover investment [12]. Regarding self-consumption, former regulation [13] stablished a specific cost to be paid as a consequence of self-consumed energy. Only low-voltage low-power prosumers who did not feed surplus energy into the grid were exempted from paying that specific cost. Additionally, self-consumption installations and energy could not be shared among prosumers, preventing the development of prosumers communities. This policy strongly discouraged the investment in new self-consumption installations. The situation has recently changed by means of a new law [14], which exempts self-consumed energy from paying any extra cost regardless of whether the prosumer feeds the excessive energy into the grid or not. Moreover, energy management can already be shared within a community. Therefore, in the absence of further regulation, current economic situation for Spanish prosumers can be summarized as the possibility of purchasing or selling energy from/to the power system at market price (no energy-based aids are planned for generated energy). In addition, payment of network tariffs for energy fed into or demanded from the grid must be paid, but no extra costs for self-consumed energy. Also, either individual or shared management are possible.

In order to maximize the advantage of self-consumption for end users, flexibility to match generated energy with demanded one is essential. This flexibility can be achieved by means of two possible mechanisms: demand-side response (DSR) and/or energy storage systems (ESS). The first one had a wide attention in literature [15,16]. As household electricity demand has a limited potential to apply restrictive DSR programs, the work described in this paper is focused on ESS usage instead, whose operation is scheduled according to different targets.

The role of ESS in microgrids is usually related to peak shaving [3], leading to a reduction of distribution system costs, which are based on the available power capacity instead of the volume of circulating energy. Other classical target is to mitigate fluctuation of PV generation [8] or other intermittent renewable energy source. ESS scheduling with economic target within a microgrid has also been discussed in literature [5,6,17,18]. Choi et al. [5] schedule a unique ESS to minimize traded energy cost based on energy price. In [6], the authors schedule batteries aiming at microgrid energy generation cost minimization, with no grid interchange. Both energy sale/purchase prices and operation and maintenance (O&M) costs of DERs are used in the optimization process in [17], although O&M costs of every DER (both renewable generation and ESS) are considered equal in this paper. Depreciation and environmental costs are also added to objective function in [18], being their values obtained from previous published papers. In all these works optimal ESS scheduling is performed and evaluated considering energy price as the only economic parameter to be considered in the interconnection of the microgrid with the main grid, i.e., to authors' knowledge, no previous work considers network tariffs to evaluate the economic advantages of an ESS scheduling method.

On the other hand, the coordination of several storage systems, owned by different prosumers, is not usually considered within a microgrid's common energy management strategy. The concept of "peer-to-peer (P2P)" supply [19,20] explains energy sharing within a community of prosumers. However, in these works, P2P supply is provided only by the generation surplus, without the involvement of stored energy. A wide review of possibilities of grouping prosumers as a community can be found in [21], which reveals that the common objectives of these communities are to maximize distributed production, to minimize losses or to optimize revenues. According to [21,22], further research is required in the area of prosumers' objectives and motivations.

The main goal of the present work is to evaluate the advantages of scheduling microgrid's ESS with an objective function based on minimizing generation-demand mismatch within the microgrid (thus minimizing energy exchange with the main grid) when compared to classical cost minimization.

Benefits are observed for both prosumers, with PV generation and ESS, and the main grid. The case study is focused on a community of prosumers under Spanish regulation. Besides the expected advantages related to self-consumption, self-sufficiency and peak shaving, also economic benefits are achieved using the proposed objective function, because it reduces the prosumers electricity bill, at least in the absence of energy-based incentives, and better preserves battery lifetime. The economic evaluation of a scheduled optimization process that does not consider economic variables in the objective function is a novel contribution of this work. Furthermore, the study has been developed aiming to prove that cooperation between community prosumers, under the concept of microgrid, improves the global economic benefit for the community, compared to an individual management.

The paper is organized as follows: Section 2 describes the case study, the optimization methodology and the objective functions tested. Results are shown in Section 3. Finally, Section 4 discusses results and summarizes the conclusions.

2. Materials and Methods

2.1. Microgrid under Study

The microgrid considered in this study consists of two dwellings with typical household electrical devices, both equipped with a PV system and a battery based ESS (see Figure 1).
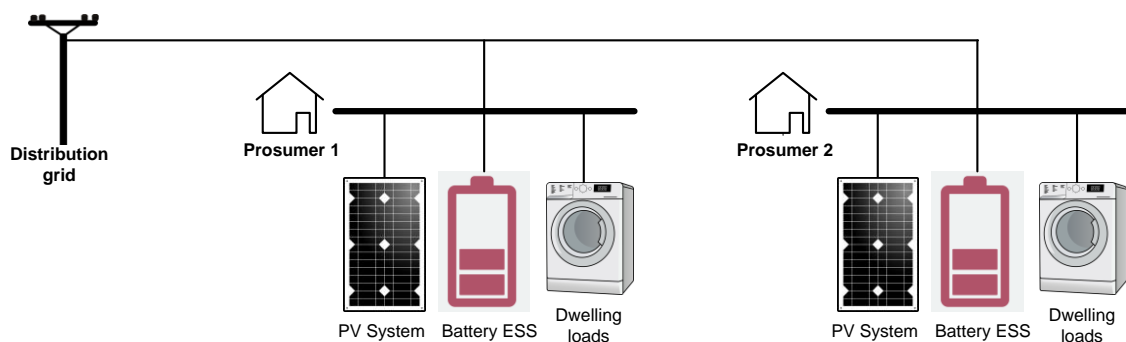
Figure 1. Schematic of the microgrid under study.

Starting from measured values in real households, demand of each house has been established considering typical residential appliances (lighting, air conditioning, washing machine, etc.) and a 4.6 kW peak power house (very common in Spanish dwellings). According to Spanish technical regulations the line capacity must be higher than the peak demand. House number 1 presents a higher demand during the 24 h of the day under study. Both houses are equipped with the same generation system and ESS (a 4 kW-rated power PV system and a battery with 6 kWh capacity and $2/-2$ kW maximum charging/discharging power). Due to the proximity of the dwellings and the same characteristics of the PV systems, the same irradiation (based on climate data from a nearby weather station) and the same PV production has been assumed for both houses. Hourly average active power, generated and demanded, is shown in Figure 2 for both houses. The profiles from Figure 2 are used by the EES energy management system, assumed as a previous day forecast. One-hour resolution has been chosen not only for being an adequate resolution for one-day-horizon demand and generation forecasting, but also due to the time resolution of published market energy prices. In the scenario shown in Figure 2 one of the households has excess generated energy whereas the other one presents excess demand compared to the produced energy. Note that neither demanded power nor generated power exceeds peak demand (4.6 kW) and therefore, power lines' capacity is not exceeded.
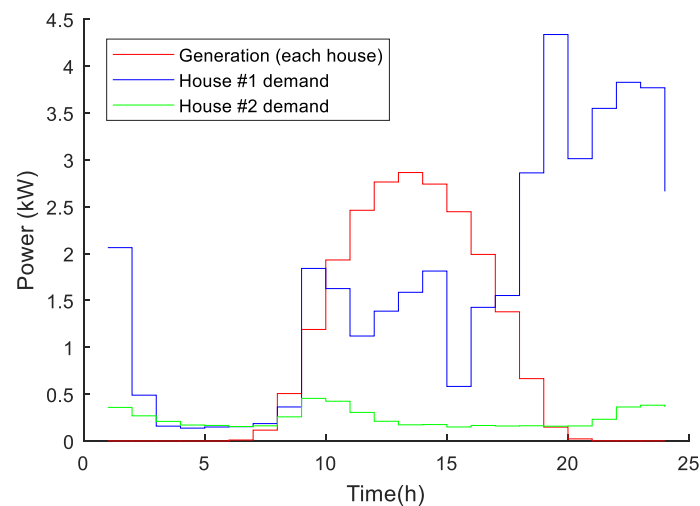
Figure 2. Generated and demanded average hourly power in both households.

2.2. Optimization Process for the Battery Scheduling

In this paper, the charging/discharging power of both batteries is scheduled with different target objectives, both in individual and in cooperative mode. The optimization process is performed using a genetic algorithm (GA) technique, as it was discussed in authors' previous work [23].

Generation and demand hourly power forecasted values (see Figure 2) of a prosumer are collected in 24-element vectors $G(t)$ and $D(t)$, $t = 1, 2, \ldots, 24$ h, respectively. In cooperative mode these vectors collect the sum of both prosumers. A 24-element vector $P_B^i(t)$, $t = 1, 2, \ldots, 24$ h, is composed of the dispatched active power schedule of prosumer's battery i. In cooperative mode all batteries within the community are considered. The adopted sign convention is positive for charging and negative for discharging. Elements $P_B^i(t)$ (hourly dispatched active power scheduled for every battery) are the values to be scheduled according to the optimization process; therefore, they will be the result of the GA technique. Original demand $D(t)$ is then modified to $D_{mod}(t)$, according to the battery contribution, as shown in Equation (1).

$$D_{mod}(t) = D(t) + \sum_i P_B^i(t). \tag{1}$$

Since batteries' charging/discharging efficiency rates present similar values, their effect has been neglected in this work.

The GA optimization process (described in [23]) finds the best solution for the elements $P_B^i(t)$. If an individual prosumer constitutes the objective to be optimized, the number of values to be obtained is 24. In a coordinated mode batteries of both prosumers are scheduled jointly, generating a vector composed of concatenated strings $P_B^1(t)$ and $P_B^2(t)$. This algorithm was programmed in MATLAB® to minimize the objective function subjected to a set of constraints, as explained below.

As previously pointed out, economic profit of prosumers is the most common optimization target addressed in literature. Energy cost is the preferred parameter to weight the scheduled battery power and, consequently, the purchased/sold energy from/to the main grid. Although this cost is not, by its own, sufficient to perform a complete optimization of the energy bill, the complexity of tariffs, premiums and prices encourages to adopt this value as weight for the objective function to be reached. As a consequence, in this work the price of traded energy is used to perform a first approach for the objective function. As discussed earlier, the purchased energy is usually paid at market prices, while the sold energy suffers from strong variations depending on the country. In Spain, currently, neither premiums nor fixed FIT are planned for energy sold by prosumers, therefore market price is also considered as the price for the sold energy. Final hourly price for each hour of an average day (average

value for a day in a whole year, between 1 December 2017 and 30 November 2018 [24]) is collected in the 24-element vector $Pr(t)$ and shown in Figure 3.
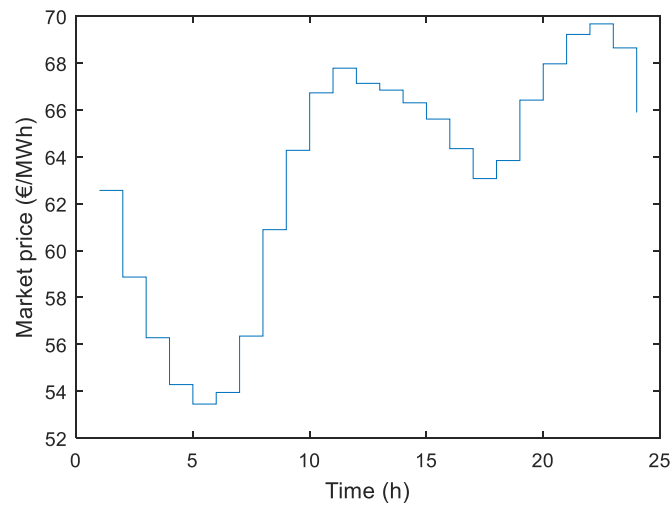
Figure 3. Spanish market yearly-average clearing price.

This preliminary approach for the objective function is called cost objective function (COF) and is determined by Equation (2), aiming to minimize energy cost where $f_{\text{cost}}(t)$ denotes the amount of money to be paid for the purchased energy minus the income received for the sold energy, at every hour $t = 1, 2, \ldots, 24$. The contribution of the batteries is included in the vector $D_{mod}(t)$, defined in Equation (1). Since PV generation and battery ESS O&M costs are not clearly related to their power scheduling, they have not been considered in the objective function:

$$f_{\text{cost}}(t) = Pr(t) \cdot [D_{mod}(t) - G(t)]. \tag{2}$$

In contrast, the novel objective function, proposed in this paper, is called mismatch objective function (MOF) and tries to improve not only the economic profit, but also the system efficiency (lower losses) and the exploitation of the DER. It intends to minimize the mismatch between generation and modified demand at every hour, i.e., the power in the interconnection with the main grid as shown in Equation (3). The square operator is introduced to penalize the highest errors. This objective function implicitly pursues self-consumption and self-sufficiency rates maximization, peak shaving, energy losses minimization in the distribution grid and network tariff costs reduction:

$$f_{mismatch}(t) = [D_{mod}(t) - G(t)]^2. \tag{3}$$

A set of constraints is added to the algorithm in order to assure safe performance and to prevent battery's early degradation. These constraints are the same in both optimization processes:

- State of charge (SoC) range: Battery manufacturers recommend keeping the SoC (percentage of charge related to the rated capacity) within a safe operational range [SoC_{min}, SoC_{max}]. Dynamic equation for SoC calculation is shown in Equation (4), under the assumption of unity charging/discharging efficiency. A discretization of Equation (4) is done in this constraint, which is shown in Equation (5), and minimum and maximum limits are assumed to be 20% and 100% respectively, taking [25] as reference:

$$SoC^i(t) = SoC^i(0) + \frac{1}{C_{nom}^i} \int_0^t P_B^i(t)dt, \tag{4}$$

$$\text{SoC}^i_{min} \leq \text{SoC}^i_{init} + \frac{\sum\limits_{t=1}^{24} P^i_B(t)\Delta t}{C^i_{nom}} \leq \text{SoC}^i_{max}. \tag{5}$$

For each battery i, C^i_{nom} is the nominal capacity (6000 Wh for both prosumers) and SoC^i_{init} is the SoC at the beginning of the day. In this study initial SoC of 83% and 50% have been considered for prosumers' batteries 1 and 2, respectively. The time interval Δt is 1 h.

- Charge/discharge power: The charging/discharging power is bounded by the battery specifications and by the battery's power electronics converter rated power. Equation (6) describes this constraint, in which $P^i_{max,dis}$ and $P^i_{max,ch}$ are the maximum allowed power for discharging and charging (-2000 W and 2000 W have been respectively assumed).

$$P^i_{max,dis} \leq P^i_B(t) \leq P^i_{max,ch}. \tag{6}$$

- Power gradient limitation: It is desirable that batteries' SoC presents a smooth variation along the day. Abrupt changes in SoC along with frequent alternating between charge and discharge modes negatively affect the battery lifetime [26,27]. Therefore, an additional constraint has been included to avoid large power oscillations between two consecutive hours. A maximum power gradient ΔP_B is considered with that purpose, as presented in Equation (7). A value of 300 W has been selected for ΔP_B, obtained from the maximum difference observed between consecutive hours in a daily profile averaged for a year in a real house.

$$\left| P^i_B(t) - P^i_B(t+1) \right| \leq \Delta P_B. \tag{7}$$

The ability of GA to search for the solution in the entire solution space and to find the global optimum solution even in non-convex, non-linear and non-smooth optimization problems has led to its use in this type of optimization problems [23,28]. This evolutionary algorithm emulates natural selection process. Starting from a random initial population of possible solutions (chromosomes) within a proper range (-2000 to 2000 W for each battery in this case study) of the solution space, GA iteratively creates new populations (children) according to their fitness for the objective function. Stopping criteria related to fitness value and computation time are included to finish the optimization procedure.

In this case study, chromosomes consist of 24 or 48 values of P_B, depending on whether individual or coordinated scheduling is being performed. The final solution will consist in the set of hourly battery charging/discharging power values which minimizes the objective function subject to defined constraints.

3. Results

The performance of the proposed algorithm with the aim of comparing the different objective functions and evaluating the advantages of prosumers' cooperation is quantified by means of usual indicators in literature. Self-consumption (SC) and self-sufficiency (SS) rates are well known indicators and they are presented in Equations (8) and (9), respectively. In both cases, the numerator computes the load instantly matched by the local production, using the considered batteries. Therefore, SC describes the percentage of on-site generation that is instantly consumed by the prosumer and SS the percentage of demand instantly satisfied by the on-site generation [29]:

$$\text{SC} = \frac{\sum\limits_{t=1}^{24} min[D_{mod}(t), G(t)]}{\sum\limits_{t=1}^{24} G(t)}, \tag{8}$$

$$SS = \frac{\sum\limits_{t=1}^{24} min[D_{mod}(t), G(t)]}{\sum\limits_{t=1}^{24} D(t)}. \tag{9}$$

Other technical indicators to evaluate the results are the power interchanged with the main grid P_{grid}, obtained from the nodal (in individual operation) or the whole system (coordinated operation) power balance, computed by Equation (10), and the accumulated energy import E_{imp} and export E_{exp} during the whole day, computed by Equations (11) and (12) respectively. One must note that P_{grid} should not be higher than the line capacity (4.6 kW for each dwelling or 9.2 kW for the common supply line):

$$P_{grid}(t) = D_{mod}(t) - G(t), \tag{10}$$

$$E_{imp} = \sum_{t=1}^{24} P_{grid}(t) \, \forall \, P_{grid}(t) > 0, \tag{11}$$

$$E_{\exp} = \sum_{t=1}^{24} P_{grid}(t) \, \forall \, P_{grid}(t) < 0. \tag{12}$$

Finally, economic indicators are used to evaluate the profitability of the obtained solution for the prosumers. Based on the energy trading prices, $Cost_{bnt}$ denotes the energy cost before network tariffs in €/day, and is calculated by Equation (13):

$$Cost_{bnt} = \sum_{t=1}^{24} Pr(t) \cdot P_{grid}(t). \tag{13}$$

$Pr(t)$ is the set of hourly prices of the Spanish Electricity Market (Figure 3). According to P_{grid} sign, the cost is positive when the energy is imported.

Network tariffs have two components for consumers in Spain: a capacity-based term, Consumer Power Tariff (CPT, in €/kW·year), which is multiplied by the contracted power (CP), and a volumetric term, Consumer Energy Tariff (CET, in €/kWh). On the other hand, a volumetric term is only established for producers, Producer Energy Tariff (PET, in €/MWh). Values for these tariff terms have been obtained from Spanish regulation for low voltage consumers, with the so-called 2.0 A tariff [30], and for any producers [31], being CPT = 38.043426 €/kW·year, CET = 0.044027 €/kWh and PET = 0.5 €/MWh.

CP can be selected as any value of power, rounded by multiples of 0.1 kW, over the maximum demanded power [14]. In each case, CP (kW) has been obtained for the day under study, starting from the maximum absolute value of P_{grid}.

These values have been used to calculate the daily cost of the electric energy after network tariffs $Cost_{ant}$ by means of Equation (14):

$$Cost_{ant} = {}^{\text{CPT} \cdot \text{CP}}/_{365} + \text{CET} \cdot \left| E_{imp} \right| + \text{PET} \cdot \left| E_{\exp} \right|. \tag{14}$$

The mentioned indicators are used to evaluate the performance of both tested objective functions (cost objective function COF and mismatch objective function MOF), to compare them with each other and with the case without ESS. Firstly, individual scheduling for each dwelling is considered, and afterwards, results are compared to the case where coordinated community management is considered.

3.1. Individual Schedule of Batteries

Taking into account the objective functions presented in Section 2, Figure 4 shows generation, initial demand and demand modified by the action of the batteries for both prosumers.

(**a**)

(**b**)

(**c**)

(**d**)
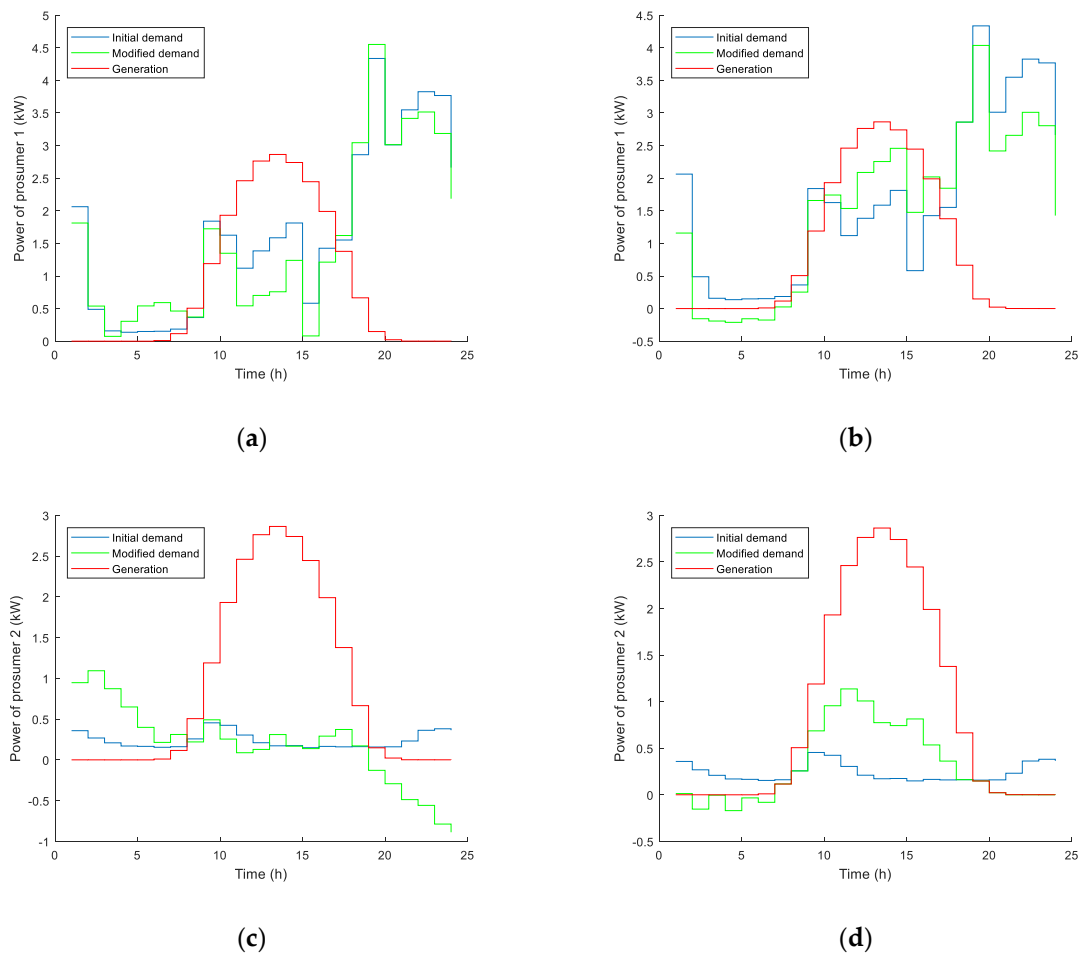
Figure 4. Generation, demand and modified demand hourly power curves during scheduled 24 h: (**a**) Prosumer 1, COF; (**b**) Prosumer 1, MOF; (**c**) Prosumer 2, COF; (**d**) Prosumer 2, MOF.

Table 1 shows the SC and SS indicators obtained with each of the proposed objective functions and the situation without ESS.
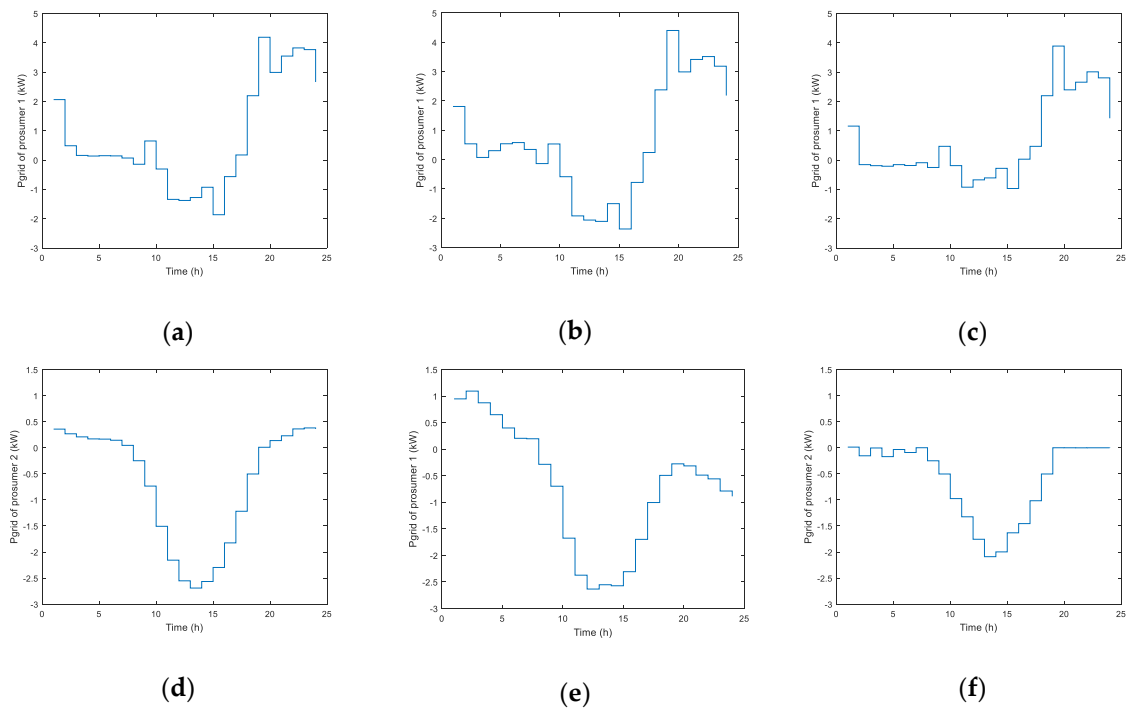
Table 1. SC and SS indicators for each of the prosumers with individual schedule.

Prosumer	Indicator	Without ESS	COF	MOF
Prosumer 1	SC	0.6327	0.4611	0.7568
	SS	0.3306	0.2410	0.3955
Prosumer 2	SC	0.1384	−0.0177 [1]	0.3427
	SS	0.5083	−0.0651 [1]	1.2582 [2]

[1] $SS < 0$ is due to negative values of $D_{mod}(t)$ in Equation (9). [2] $SS > 1$ means that imported energy is higher than household daily demand.

As it was expected, COF leads prosumers to buy energy at night (when the price is low) and to avoid buying or even to sell energy at evening peak price hours. This procedure has economic advantages in energy cost but penalizes SC and SS rates, as shown in Table 1. These indicators are even worse with COF than those obtained without ESS in the households. On the contrary, MOF significantly improves SC and SS of both prosumers, since its main target is to match generated and demanded power as much as possible.

Figure 5 shows the power interchanged with the main grid P_{grid}, according to Equation (10). It can be observed that line capacity of each dwelling is not exceeded in any cases.

Figure 5. P_{grid} during scheduled 24 h (positive values for import energy flow and negative for export):
(**a**) Prosumer 1, without ESS; (**b**) Prosumer 1, COF; (**c**) Prosumer 1, MOF; (**d**) Prosumer 2, without ESS;
(**e**) Prosumer 2, COF; (**f**) Prosumer 2, MOF.

Absolute values for energy imported E_{imp} and exported E_{exp} (according to Equations (11) and (12) respectively), are reported in Table 2.

Table 2. Energy import and export for each of the prosumers with individual schedule.

| Prosumer	Indicator	Without ESS	COF	MOF
Prosumer 1	$\lvert E_{imp}\rvert$ (kWh)	27.203	27.047	20.495
	$\lvert E_{exp}\rvert$ (kWh)	7.801	11.445	4.893
Prosumer 2	$\lvert E_{imp}\rvert$ (kWh)	2.844	4.361	0.014
	$\lvert E_{exp}\rvert$ (kWh)	18.297	21.614	13.952

Figure 5 and Table 2 confirm the conclusion previously reached. The dependence of both prosumers on the main grid can be, when COF is used, even higher than in the absence of ESS (either in terms of power or energy). This is a consequence of considering energy price as the unique variable to perform the battery management and leads to other drawbacks, such as higher required capacity of the distribution grid and higher transmission losses. However, MOF reduces the dependence on the main grid, both in power and energy terms, thus assuring advantages also for the distribution system. The previous indicators used for evaluating the performance of the proposed objective functions are related to technical performance. Table 3 below summarizes the economic indicators to evaluate eventual prosumer benefits.

Table 3. Economic indicators for each of the prosumers with individual schedule.

Prosumer	Indicator	Without ESS	COF	MOF
	CP (kW)	4.2	4.4	3.9
Prosumer 1	$Cost_{bnt}$ (€/day)	1.2959	1.0258	1.0610
	$Cost_{ant}$ (€/day)	2.9351	2.6809	2.3723
	CP (kW)	2.7	2.6	2.1
Prosumer 2	$Cost_{bnt}$ (€/day)	−1.0278	−1.1826	−0.9135
	$Cost_{ant}$ (€/day)	−0.6120	−0.7088	−0.6871

Table 3 proves that MOF presents economic advantages as well. Although $Cost_{bnt}$ is obviously lower when COF is used, this approach leads to higher energy interchange with the grid, which adds costs in terms of network tariffs both when importing and exporting energy (although with different unitary cost). In the case of MOF, CP is reduced as well as imported and exported energy, leading to considerably lower network tariffs. As a consequence, this is the approach with the lowest $Cost_{ant}$ for prosumer 1 and produces similar revenues for prosumer 2.

Additional benefits are obtained from MOF related to batteries lifetime. As discussed earlier, a higher frequency of charge/discharge cycles increases battery degradation, leading to a lifetime decrease. Figure 6 compares batteries' SoC evolution when the different objective functions are used. It can be observed that oscillation between charge/discharge modes is less frequent using MOF than using COF, thus contributing to slow down battery degradation.

(**a**)

(**b**)

(**c**)

(**d**)
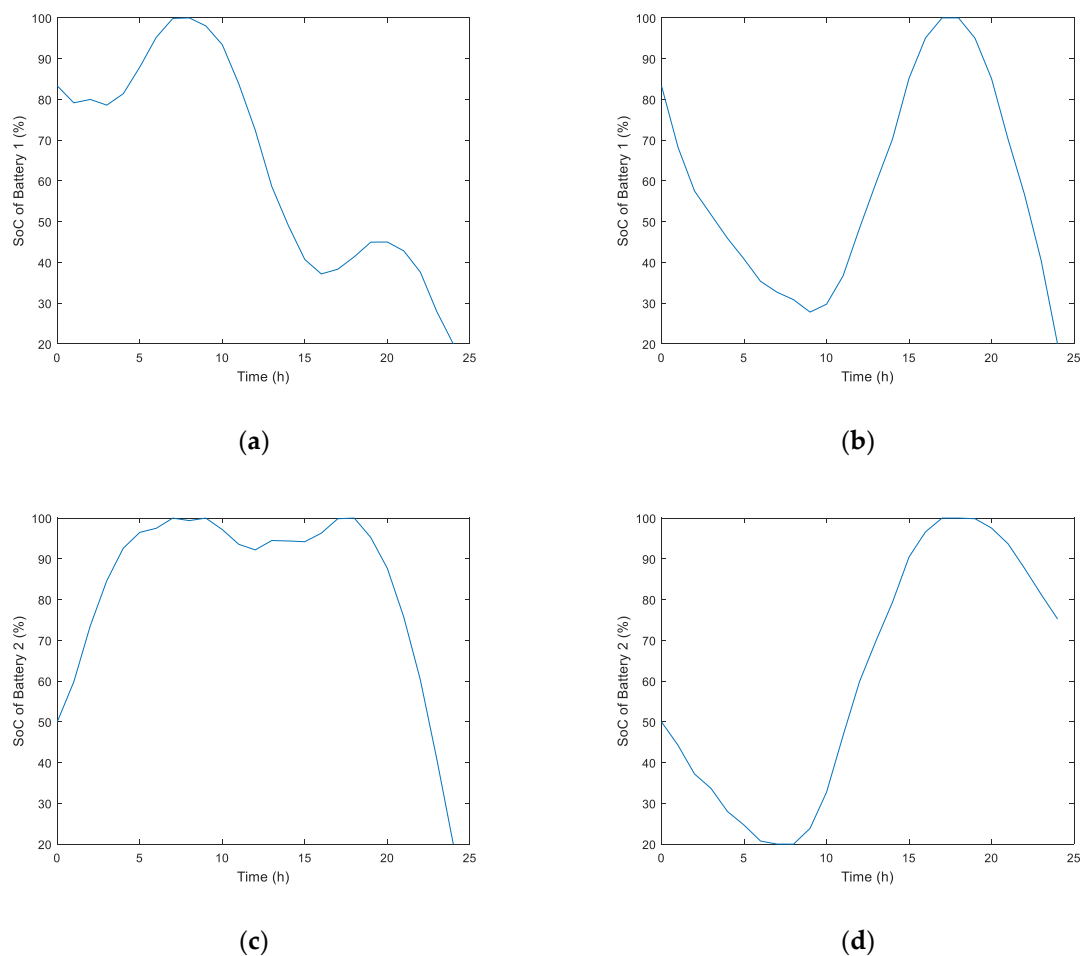
Figure 6. SoC of batteries during scheduled 24 h: (**a**) Prosumer 1, COF; (**b**) Prosumer 1, MOF; (**c**) Prosumer 2, COF; (**d**) Prosumer 2, MOF.

3.2. Coordinated Schedule of Batteries

At this stage, both prosumers are considered as one management unit (prosumers community), under the concept of microgrid, where DERs are shared to reach a joint optimization target. In this case, the output vector to be obtained, P_B, by means of the GA is composed of 48 values, corresponding to the 24 h scheduling of both batteries, while constraints are still applied to each of the batteries. The obtained results are shown below, with the aim of comparing this scenario to the individual management of each prosumer.

Figure 7 shows generation, initial demand and demand modified by the action of batteries, with both objective functions. It is important to note that these results refer to the whole microgrid.


(a)

(b)
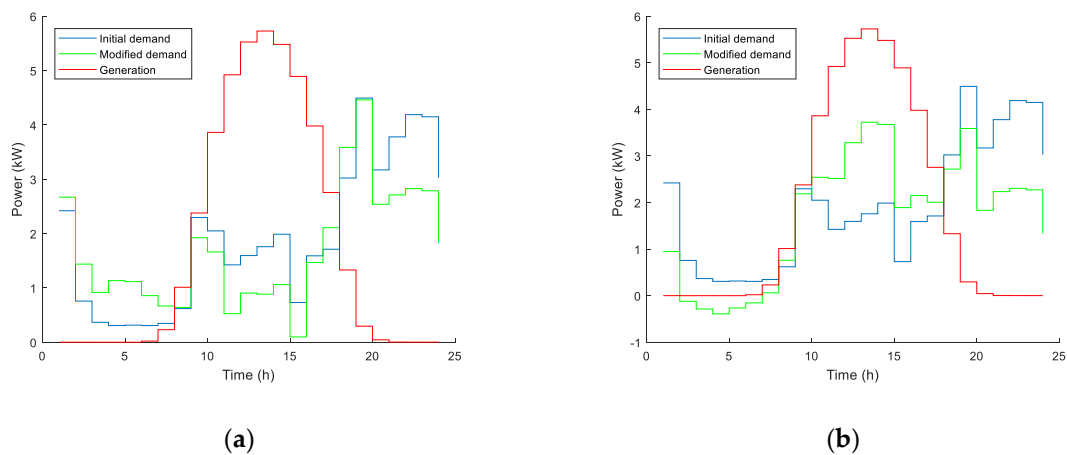
Figure 7. Generation, demand and modified demand hourly power curves of the whole microgrid, during scheduled 24 h: (**a**) COF; (**b**) MOF.

SC and SS indicators obtained for each objective function and for the situation without ESS can be found in Table 4. The same conclusions can be drawn as in the case of individual scheduling of batteries: MOF improves both SC and SS indicators, whereas they reach lower values when COF is used. This is due to a higher dependence on the main grid in this last case, as it is also shown in Figure 8 and Table 5.

Table 4. SC and SS indicators for the whole microgrid with coordinated scheduling.

Indicator	Without ESS	COF	MOF
SC	0.4168	0.3112	0.5950
SS	0.3814	0.2847	0.5444

(a)

(b)

(c)
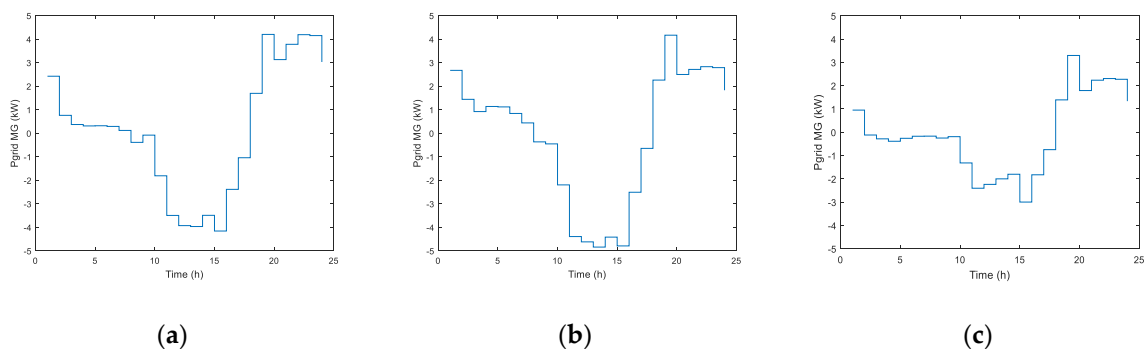
Figure 8. P_{grid} of the whole microgrid during scheduled 24 h (positive values for export energy flow and negative for import): (**a**) Without ESS; (**b**) COF; (**c**) MOF.

Table 5. Energy import and export for the whole coordinated microgrid.

| Indicator	Without ESS	COF	MOF
$|E_{imp}|$ (kWh)	28.720	27.606	15.553
$|E_{exp}|$ (kWh)	24.771	29.257	17.204

Both power and energy interchange with the main grid are significantly improved when MOF is used. Note that P_{grid} is always far from the capacity of the common supply line (9.2 kW). In the case of COF, energy import is reduced in comparison to the case without ESS, but energy export is increased, since only economic factors are considered to reach the optimal solution.

The economic indicators are shown in Table 6, where the sum of both prosumers' costs with individual schedule has been added for comparison.

Table 6. Economic indicators for the whole microgrid, and individual CP and sum of both prosumers costs with individual schedule.

Type of Schedule	Indicator	Without ESS	COF	MOF
Coordinated (whole microgrid)	CP_{MG}(kW)	4.2	4.8	3.3
	$Cost_{bnt}$ (€/day)	0.2680	−0.1604	−0.0756
	$Cost_{ant}$ (€/day)	1.9826	1.5700	0.9617
Individual (sum of both prosumers)	CP_1/CP_2 (kW)	4.2/2.7	4.4/2.6	3.9/2.1
	$Cost_{bnt}$ (€/day)	0.2681	−0.1568	0.1475
	$Cost_{ant}$ (€/day)	2.3231	1.9721	1.6852

A very interesting conclusion can be drawn from Table 6. MOF also improves the economic profit of the microgrid in comparison to COF and moreover it significantly reduces the cost of the electricity bill for the whole microgrid compared to individual schedule of the battery of each prosumer. Obviously, the advantage is for the set of prosumers, as each of them is not equally affected. Prosumer 2 is a net energy exporter and earned money along the day (see Table 3). Therefore, if equitable share is done of the whole microgrid bill, this prosumer would be adversely affected. A fair rule based on energy balance of each prosumer should be developed to assign costs to each prosumer of the microgrid, as proposed in [21]. Regarding the evolution of battery SoC, Figure 9 depicts those regarding both objective functions, showing that MOF also reduces battery degradation.

(**a**)   (**b**)
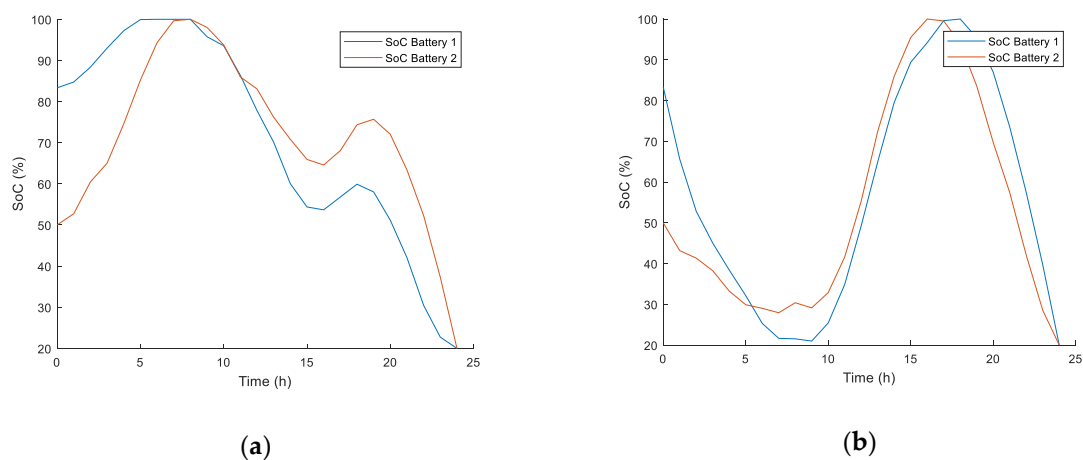
Figure 9. SoC of batteries during scheduled 24 h: (**a**) COF; (**b**) MOF.

The previously tested case study presented the advantages of batteries' coordinated scheduling in comparison to individual operation. In this case study, different demand levels have been considered to evaluate distinct performance between both operation modes. The proposed objective function was

also tested using for both prosumers the average yearly demand profile obtained from a real measured dwelling. Figure 10 and Table 7 depict the generation, demand and modified demand of the whole microgrid and the main performance indicators obtained for this new case study, respectively.


(a)   (b)
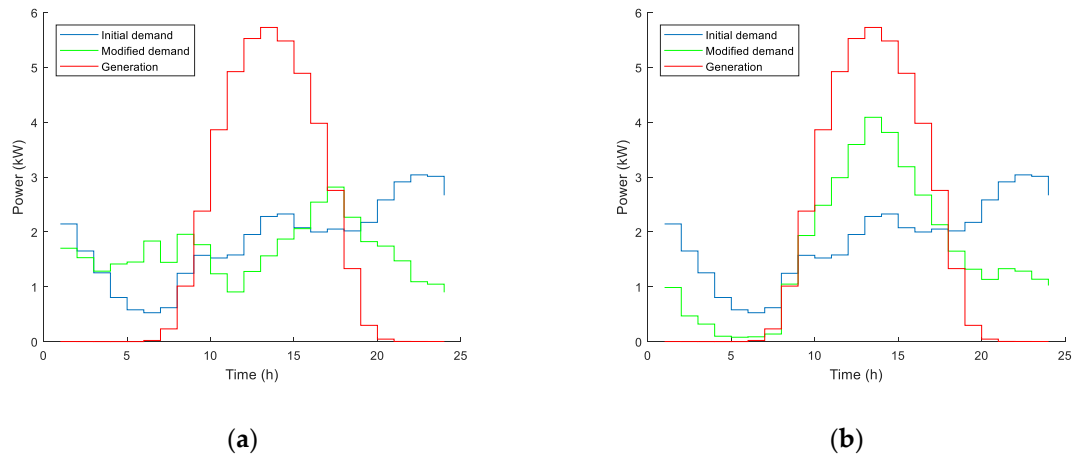
Figure 10. Generation, demand and modified demand hourly power curves of the whole microgrid, during scheduled 24 h, in the new case study: (**a**) COF; (**b**) MOF.

Table 7. SC and SS rates, energy import and export and economic indicators for the whole coordinated microgrid, in the new case study.

Indicators	Without ESS	COF	MOF
SC	0.4783	0.4456	0.7004
SS	0.4555	0.4244	0.6671
$|E_{imp}|$ (kWh)	24.285	20.071	9.248
$|E_{exp}|$ (kWh)	22.161	23.547	12.724
CP (kW)	3.6	4.2	1.9
$Cost_{bnt}$ (€/day)	0.1059	-0.3326	-0.2308
$Cost_{ant}$ (€/day)	1.5614	1.0006	0.3807

P_{grid} and the evolution of the SoC of batteries are also shown in Figures 11 and 12 respectively.

(a)   (b)   (c)
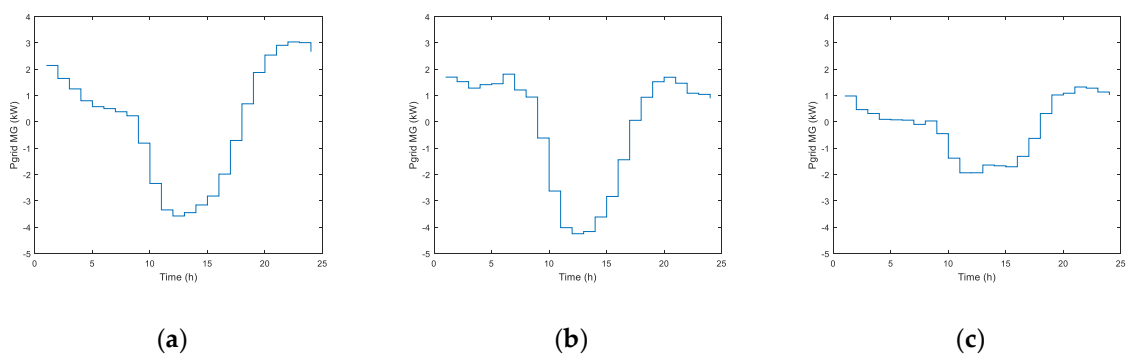
Figure 11. P_{grid} during scheduled 24 h (positive values for export energy flow and negative for import), in the new case study: (**a**) Without ESS; (**b**) COF; (**c**) MOF.

This new case study demonstrates that the proposed objective function, in a measured average demand situation, clearly outperforms the objective function based on energy cost in all the parameters previously discussed. It improves SC and SS indicators, significantly reduces the interchanged power and energy, decreases electricity bill and better exploits battery capacity, reducing the number of charging/discharging cycles a day.
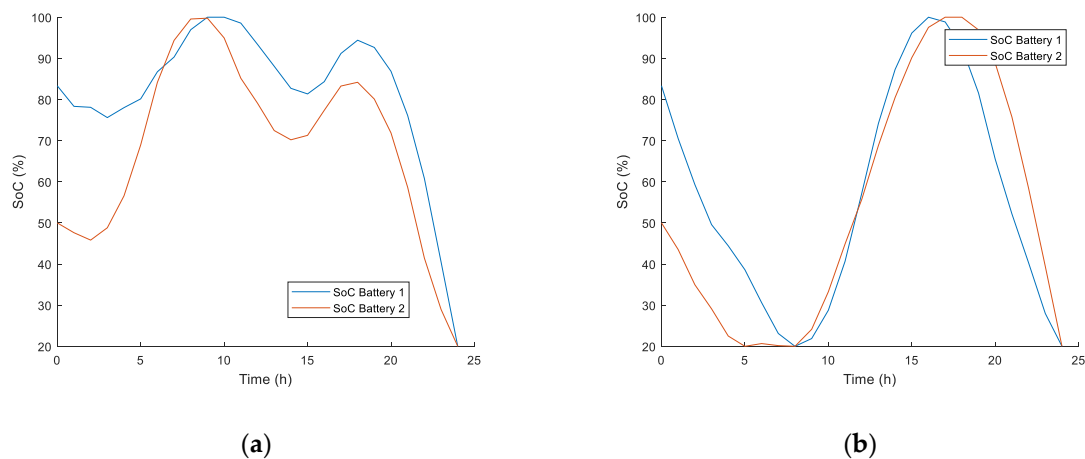
Figure 12. SoC of batteries during scheduled 24 h, in the new case study: (**a**) COF; (**b**) MOF.

4. Discussion and Conclusions

In this paper a microgrid of prosumers with PV generation and battery ESS is managed using a GA to schedule the batteries' charging/discharging power in a daily timeframe with one-hour resolution. Two management strategies were tested: individual and coordinated scheduling. Moreover, two objective functions were evaluated and compared. The first one (COF) aims to minimize the cost associated with energy consumption, while the second one (MOF) is focused on improving both SC and SS indices.

Regarding objective functions, the proposed MOF outperforms COF, which is based on traded energy price. This improvement is mainly reached in terms of SC and SS rates, and in the interconnection power and energy with the main grid. As a consequence, a better exploitation of DER is achieved, along with a lower impact into the distribution grid, both in capacity (which must be enough to match peak power) and in losses (which are related to the volume of flowing energy). But also economic advantages are shown when this new objective function is used comparing to an objective function based on the cost of the traded energy. Although COF leads to lower energy cost, before network tariffs, it also causes an increase in the required CP and in the daily imported and exported energy, thus increasing networks tariffs. This conclusion is valid in the absence of support for surplus energy of self-consumers, which tends to be the policy in European countries once grid-parity for the activity has been achieved. Finally, battery cycling is favorable to avoid premature degradation, as only one charge/discharge cycle is completed during the day with MOF, unlike the result of using COF. Results obtained from this study conclude that reducing the dependence on the main grid, both in power and energy terms, not only improves energy efficiency, distribution losses, exploitation of DERs and empowers consumers, but also economic advantages are reached for prosumers both in the electricity bill and battery lifetime. Therefore, this objective outperforms classical cost minimization techniques widely proposed in literature.

Another important conclusion is attained related to microgrid coordination. Performing the schedule of batteries as a set of resources to jointly optimize the microgrid energy management shows a noticeable improvement compared to individual scheduling, in terms of power and energy interchanges as well as economic benefits. Coordinated schedule of prosumers with average demand also shows clearly higher benefits when MOF is used instead of COF. This case study represents a realistic self-consumption situation and conclusions can be easily extended to bigger communities with several household prosumers. This result reinforces the interest for microgrids and smart communities as a way to improve energy efficiency and exploitation of DER. An effective method for assigning the resulting total costs of the microgrid to each of the prosumers is pending for future research.

Nomenclature

CET:	Consumer Energy Tariff
C^i_{nom}:	Nominal capacity of battery i
COF	Cost objective function
$Cost_{ant}$:	Cost after network tariffs
$Cost_{bnt}$:	Cost before network tariffs
CP	Contracted Power
CP_i:	Contracted Power of prosumer i
CP_{MG}:	Contracted Power of the whole microgrid
CPT	Consumer Power Tariff
$D(t)$:	Demanded power at hour t
DER	Distributed Energy Resource
$D_{mod}(t)$:	Modified demand at hour t
DSR	Demand-Side Response
E_{exp}:	Exported energy along the whole day
E_{imp}:	Imported energy along the whole day
ESS	Energy Storage System
f_{cost}:	Fitness function to be minimized according to COF
FIT	Feed-in Tariffs
$f_{mismatch}$:	Fitness function to be minimized according to MOF
$G(t)$:	Generated power at hour t
GA	Genetic Algorithm
MOF	Mismatch objective function
O&M	Operation and Maintenance
P2P	Peer-to-Peer
$P_B^i(t)$	Battery power of battery i at hour t
PET	Producer Energy Tariff
P_{grid}:	Power in the interconnection with the main grid
$P^i_{max,ch}$:	Maximum charge power for battery i
$P^i_{max,dis}$:	Maximum discharge power for battery i
$Pr(t)$:	Energy market price at hour t
PV	Photovoltaic
SC	Self-Consumption rate
SoC	State of Charge
SoC^i_{init}:	State of Charge of battery i at the beginning of the day
SoC^i_{max}:	Maximum allowed State of Charge of battery i
SoC^i_{min}:	Minimum allowed State of Charge of battery i
SS	Self-Sufficiency rate
ΔP_B:	Maximum power gradient between consecutive hours

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