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Techno-economic Assessment of Centralized and Decentralized Energy Management Strategies for Energy Sharing in Collective Self-consumption Schemes

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Corresponding Author:	Ane Feijoo-Arostegui Ikerlan Technological Research Centre Arrasate/Mondragón, Guipuzcoa SPAIN
First Author:	Ane Feijoo-Arostegui
Order of Authors:	Ane Feijoo-Arostegui
	Luís Rodrigues
	Haizea Gaztañaga
	José Villar
	Tiago Soares
	Ander Goikoetxea
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Techno-economic Assessment of Centralized and Decentralized Energy Management Strategies for Energy Sharing in Collective Self-consumption Schemes

Ane Feijoo-Arostegui[a,c*], Luís Rodrigues[b], Haizea Gaztañaga[a], José Villar[b], Tiago Soares[b], Ander Goikoetxea[c]

[a] Energy Storage and Power Electronics Department, IKERLAN Technology Centre, Basque Research and Technology Alliance (BRTA), P.º J:M. Arizmendiarrieta, 2, 20500 Arrasate/Mondragón, Spain

[b] INESC TEC, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

[c] Electronic and Computing Department, Faculty of Engineering, Mondragon Unibertsitatea, Loramendi 4, 20500 Arrasate/Mondragón, Spain

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Abstract

The increasing deployment of individual and collective self-consumption systems is reshaping Energy Management Systems (EMSs) under evolving regulatory frameworks. This paper presents a techno-economic comparison between a centralized EMS and a decentralized EMS for flexible resources dispatching and sharing under collective self-consumption schemes. The centralized EMS is formulated as a Mixed-Integer Non-Linear Programming (MINLP) optimization problem, whereas the decentralized EMS employs a rule-based algorithm that requires no information exchange among members. Both strategies have been evaluated under the Spanish regulatory framework, a) using fixed allocation

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[*] Corresponding author
Email address: afeijoo@ikerlan.es (Ane Feijoo-Arostegui)

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Results indicate that both EMS architectures achieve comparable energetic performance. The centralized EMS achieves the highest levels of self-consumption, self-sufficiency and energy sharing, particularly when proportional allocation coefficients are used, while the decentralized EMS performs closely. From an economic perspective, the centralized EMS provides the highest cost reductions, while the decentralized EMS yields lower economic savings but with significantly less computational effort, with runtimes up to eighteen times shorter. These findings highlight a clear trade-off between economic optimality and computational efficiency, positioning decentralized EMS solutions as a scalable and privacy-preserving alternative for individual self-consumers transitioning to collective self-consumption schemes in evolving regulatory frameworks.

Keywords: Allocation coefficient, collective self-consumption, distributed energy resource, energy management system, peer-to-peer market.

1. Introduction

The European Union's decarbonization objectives of a 55% reduction in CO_2 emissions by 2030 and climate neutrality by 2050 are accelerating the energy transition [1]. This will require a massive integration of renewable energy sources (RES) into the energy generation mix, with the decentralization of the energy system playing a key role, driven by self-consumption regulations and the development and deployment of distributed energy resources (DERs). According to [2], [3] distributed and decentralized solar photovoltaic generation (PV) will become the largest renewable capacity source by 2030.

In this way, the RePowerEU Plan required Member States to accelerate the transposition of the Electricity Directive to enable consumers to actively engage in energy markets either exercising individual self-consumption (ISC) activities, or within collective self-consumption (CSC) schemes or energy communities, by generating, self-consuming, selling, or sharing renewable energy within CSC structures [4]. These initiatives are boosting the deployment of decentralized PV through rooftop panel installation [5]. Indeed, self-consumption reduces end-users' electricity cost, allowing them to use self-generated renewable energy, enhancing their energy independence, and lowering their environmental footprint. It also empowers users by giving them greater control over their energy usage and opens opportunities to sell or share surplus energy, particularly within CSC structures. Furthermore, self-consumption also contributes to reducing net and peak demand and can help minimizing transmission losses by incentivizing local energy balancing from local generation. Moreover, CSC can enhance grid flexibility by aggregating their members’ flexibility and participating in demand response and balancing services, among others [6],

[7], [8], [9], [10]. Although self-consumption regulatory frameworks vary considerably across European countries, restricting regulations may sometimes constrain the deployment of CSC structures. In this way, their overall potential is reduced, and the socioeconomic and grid-related benefits are diminished by establishing limiting constraints and not providing flexible enough energy sharing mechanisms. These disparities are exemplified by the Iberian Peninsula scenario, where Spain has a significantly less advanced regulatory framework than Portugal's, as described in [11].

1.1 Self-consumption regulatory framework

Regional regulatory frameworks in both Portugal and Spain define two main modalities of self-consumption under harmonized principles, as established by Portuguese Decree-Law 15/2022 [12] and Spanish legislation, including Law 24/2013 [13], Royal Decree-Law 15/2018 [14], and Royal Decree 244/2019 2019 [15] (see also [11] for a detailed comparison). ISC is defined as the act of a final consumer producing its own electricity from RES for its own use, with the possibility of either storing the surplus energy or injecting it into the grid. CSC refers to a group of consumers who, subject to defined proximity rules, come together to produce renewable energy for their own use and to share any surplus with other CSC members according to mutually agreed rules. In the case of Spain and Portugal, their regulatory frameworks are differentiated by the adoption rules, energy-sharing mechanisms and renewable generation surplus treatment [11], [16], [17], [18], [19], [20].

Regarding energy-sharing mechanisms within CSC schemes, the Spanish regulatory framework is more restrictive than the Portuguese counterpart. In both countries, the allocation of renewable energy generated in CSC schemes among participants can be explained with the so-called allocation coefficients (ACs). Under the Spanish framework, allocation is based on fixed ACs (according to the meaning in [11]), meaning that each generation facility participating in a CSC must define, before the CSC operation, a specific AC for each consumer and for every settlement period (ISP), which in Spain is hourly. These ACs must be submitted to the distribution system operator (DSO) during the licensing process, in accordance with the collective agreement of the CSC members. Two main types of fixed ACs are regulated: a) those called fixed by the Spanish regulation, which in fact means they remain constant throughout the entire year; and b) those called variable, which are in fact fixed in the sense of [11], but allowing time discrimination on an hourly basis. In both cases, AC must be pre-defined and submitted at licensing time and can be modified only once every four months. If no specific allocation methodology is selected, the DSO will apply a default scheme of fixed ACs, whereby the energy is allocated proportionally to each participant's contracted power.

Conversely, the Portuguese framework defines ACs based on a 15-minute ISP and permits a wider range of ACs: a) fixed ACs (in the sense of [11]) that define how the aggregated local surplus is shared with the consuming CSC member, corresponding to both the fixed and variable Spanish AC options, being also defined a priori and allowing time discrimination, and b) those called post-delivery ACs in [11], since they are computed after the energy measurements become available, [11], which are a) proportional-to-consumption, or b) dynamic. For the Portuguese fixed ACs, if a CSC member does not consume during a given interval, the DSO recalculates the ACs of those members consuming proportionally to the initial AC, so that they always add up to one, something not considered in the Spanish regulation. In the proportional-to-consumption ACs, the DSO allocates the energy surplus among the consuming CSC members proportionally to their consumption, according to their verified smart meter measurements. Finally, in the dynamic ACs framework, the ACs, (that are bilateral and link members with surplus to members consuming) are computed, after the energy delivery, by the CSC manager (EGAC under the Portuguese regulation) based on predefined sharing rules and sent to the DSO that validates and applies them to compute the final energy allocation.

The treatment of renewable energy surpluses in Spain depends on the self-consumption modality: either the surplus energy is compensated in the electricity bill at a price negotiated between the consumer and the retailer (only allowed for self-consumption systems with a total installed capacity below 100 kW), or the surplus energy is directly sold on the electricity market, in which case the installation is classified as a generating plant and is subject to the corresponding regulatory and market obligations (such as guarantees), constituting a large barrier for small facilities. In Portugal, both ISC and CSC schemes are allowed to sell the electricity surplus through private peer-to-peer (P2P) transactions, bilateral contracts, or in organized electricity markets (where market obligations such as guarantees also apply). For ISC, surplus energy can be sold to an aggregator or market facilitator. In the case of CSC, all surplus energy generated by the CSC members must be aggregated by the CSC manager and then sold to an aggregator or directly to the market.

1.2 CSC schemes control architecture

Recent literature has increasingly addressed the challenges and solutions for managing CSC schemes under different regulatory frameworks. A significant portion of this research focuses on the design of energy management systems (EMSs) for the adoption of flexible DERs in CSC schemes and scheduling the flexible assets to minimize the CSC cost.

Most existing literature focuses either on countries with relatively flexible regulatory frameworks or on idealized scenarios that allow for dynamic optimization of ACs. In contrast, EMSs for CSC under restrictive regulatory conditions remain underexplored. A key example is Spain, one of the focus countries of this article, where current regulations require ACs to be defined during the licensing period, preventing any dynamic adjustment thereafter. This rigidity poses a significant barrier to the broader deployment of CSC schemes.

A summary of the literature review is collected in Table 1, where works [20], [21], [22], [23], [24], [25], [26] and [27] are classified with respect to their regulatory framework country, their control architecture typology, the deployed EMS algorithm and the ACs calculation approach.

Table 1: Summary of the literature review.

Reference	Regulatory framework	Control architecture type	EMS algorithm	AC calculation
[20]	Portugal, Italy	Centralized	MILP	Ex-post (IT), dynamic (PT)
[21]	France	Centralized	Rule-based, optimization-based	Ex-post
[22]	France	Centralized	LP	Ex-post
[23]	Spain	Centralized	Genetic algorithm	Fixed, dynamic
[24]	Spain	Centralized	Rule-based	Fixed, dynamic
[25]	Spain	Centralized	Rule-based, sequential least squares optimization	Fixed, dynamic
[26]	Spain	Centralized	Genetic algorithm	Fixed (updated every 4 months)
[27]	France	Centralized, Distributed	Convex programming, Game theory	Fixed

Given this context, it is highly relevant to evaluate regulatory approaches adopted in more advanced frameworks, such as in Portugal, to identify measures that could be adapted to the Spanish case with regulatory adjustments. However, there is a clear gap in the literature regarding the design of effective EMSs that operate within such fixed frameworks. Although some studies address optimal allocation or focus on post energy delivery settlement mechanisms, they tend to overlook the practical and regulatory challenges involved in managing individual energy distribution when ACs are fixed and must be determined in advance.

This article addresses the aforementioned gap with a techno-economic evaluation of the transition from ISC to CSC with two different EMSs approaches within the Spanish regulatory framework, but considering improvements based on the Portuguese regulation. First, a specific case study is defined with potential ISC DERs embracing CSC schemes, including the optimization of the fixed ACs based on clustering methods applied to historical CSC members data, which must be done at licensing time. Then, the implications for ISC installations adopting a CSC scheme are assessed using both centralized and decentralized EMS approaches, with the objective of comparing energetic and economic performance indicators. As a next step, to assess the inefficiency of the regulated Spanish AC framework, selected measures from the Portuguese regulatory framework are integrated to improve techno-economic outcomes and stakeholder engagement. Finally, the operation of both EMSs is evaluated and compared over a one-year simulation period, analysing key performance indicators (KPIs) such as economic savings, computational costs, and system performance, among others. The main contributions of this paper are the following:

- Evaluation of the implications of CSC adoption for ISC installations under the Spanish regulatory framework, with only pre-delivery (fixed) AC, compared to using post-delivery AC as in the Portuguese context;
- Development and comparison of a centralized and a decentralized EMSs for CSC within an ex-ante (fixed) AC computation;
- Techno-economic assessment and comparison of the centralized and decentralized EMSs approaches.

The rest of the paper is organized as follows. Section 2 describes the methodology, presenting the AC calculation, the developed centralized and decentralized EMSs approaches, and the settlement. Section 3 presents the case study for the CSC scenario, and Section 4 presents and discusses the main results. Finally, Section 5 presents the key conclusions.

2. Methodology for energy sharing and management in collective self-consumption schemes

Given the strong national effort and financial incentives for residential buildings (RB) and large tertiary buildings (LTB) self-consumption deployment in Spain (PNIEC [28]), these installations are included in the present study, as depicted in Figure 1. Under this framework, the selected DERs (i.e. self-consumption installations) are well-positioned to adopt CSC schemes in future phases, thereby enhancing their energy and economic benefits. The methodology adopted in this study comprises four main components designed to evaluate the performance of different energy sharing configurations within a CSC scheme. First, ex-ante ACs are computed during the licensing period. Second, a centralized EMS is developed to optimize energy flows within the CSC, leveraging global information to achieve system-wide efficiency and cost-efficient energy allocations. Third, a decentralized rule-based EMS is developed, where each member operates autonomously according to predefined rules, enabling local decision-making with neither centralized coordination nor real-time assets data sharing. This approach is an improved version of the ISC scenario, although it is not as optimal as the centralized EMS. Fourth and last, the settlement is computed to provide the individual and collective bill calculations.

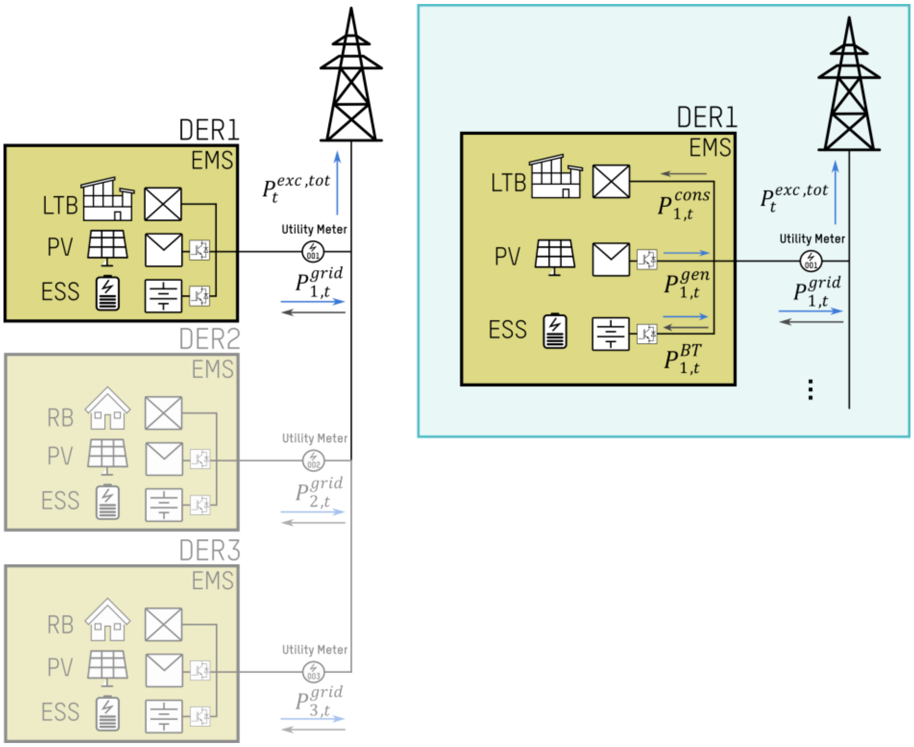

Figure 1: Assumed DER technologies for CSC.

2.1 *Ex-ante Allocation Coefficient definition*

Within the Spanish regulatory framework, at CSC licensing time, the CSC must provide the ACs that will be used to share the production of each generation unit with the CSC members. In order to boost the CSC deployment, one modification is implemented in this function: the AC is applied to the energy surplus of each DER after its self-consumption. In this way, each DER self-consumes from its own installation and shares only the excess energy. On this basis, this block computes the optimal fixed ACs for each DER using historical data of each DER, such as generation, consumption, grid electricity consumption price and surplus energy injection price. To limit complexity, optimal ACs are computed for four representative operation patterns. These patterns come from the k-medoids clustering algorithm applied to four scenarios built combining two dimensions of variability: a) working days versus non-working days, and b) summer versus winter periods. This classification captures both behavioural differences in demand and seasonal variations in PV generation, because consumption is particularly sensitive to the nature of the end-user, and PV generation has a dependency on the weather. Unlike k-means, which generates centroids as mathematical averages that do not correspond to real daily profiles, k-medoids always selects actual observations from the dataset as cluster representatives, particularly relevant when working with energy profiles to avoid smoothing demand peaks or distort the variability of PV generation. In addition, k-medoids is less sensitive to outliers, thereby ensuring that the resulting clusters remain robust and realistic [29], [30], [31], [32], [33].

Once the representative profiles of each DER have been obtained for all scenarios, the ISC-oriented EMS (developed in [34]) is run for each DER to estimate the amount of energy available for sharing. The ISC-oriented EMS [34] aims to increase the self-sufficiency of each DER by controlling the existing energy storage systems (ESS), giving the individually optimal operation profiles of each DER. To compute the ACs, a mixed-integer linear programming (MILP) based optimization is applied to each representative pattern to minimize the CSC energy cost, as expressed in (1).

$$\min_{\forall n \in N, \forall t \in T} Cost_{CSC} = \sum_{n=1}^{N} \left(\sum_{t=0}^{T} \left(C_{n,t}^{imp,grid} + C_{n,t}^{imp,P2P} - C_{n,t}^{exp,grid} - C_{n,t}^{exp,P2P} \right) \right) \tag{1}$$

where $C_{n,t}^{imp,grid}$ and $C_{n,t}^{imp,P2P}$ are, respectively, the costs of the energy bought from the grid and the energy bought within the CSC, for $n \in N$ where set N is the total number of CSC members at each sample time t of the horizon T of the representative pattern, both in [€]. Conversely, $C_{n,t}^{exp,grid}$ is the compensation for injecting energy into the grid in [€] and $C_{n,t}^{exp,P2P}$ is the revenue obtained from sold energy within the CSC in [€].

The cost of buying electricity from the retailer, (2), is the import cost of purchasing energy from the grid, $C_{n,t}^{imp,grid}$ in [€] minus the income from the energy exported to the grid, $C_{n,t}^{exp,grid}$ in [€]. These costs are calculated according to (3) and (4), respectively.

$$C_{n}^{retailer} = \sum_{t=0}^{T} C_{n,t}^{imp,grid} - C_{n,t}^{exp,grid} \tag{2}$$

$$C_{n,t}^{imp,grid} = \lambda_{n,t}^{imp,grid} \cdot P_{n,t}^{imp,grid} \cdot \Delta t \tag{3}$$

$$C_{n,t}^{exp,grid} = \lambda_{n,t}^{exp,grid} \cdot P_{n,t}^{exp,grid} \cdot \Delta t \tag{4}$$

where $\lambda_{n,t}^{imp,grid}$ is the price of the energy consumed from the grid in [€/kWh] and $P_{n,t}^{imp,grid}$ in [kW] the power imported from the grid during Δt [h], assumed both constant during this interval. Similarly, the $\lambda_{n,t}^{exp,grid}$ is the price received for the energy exported to the grid in [€/kWh] and $P_{n,t}^{exp,grid}$ in [kW], the power injected into the grid during Δt. It was assumed that $\lambda_{n,t}^{imp,grid}$ is the Spanish regulated electricity tariffs (called voluntary price for the small consumer, PVPC [35]) and that $\lambda_{n,t}^{exp,grid}$ is the pool price.

The cost of the electricity traded within the CSC (C_n^{P2P}) is the cost $C_{n,t}^{imp,P2P}$ of the purchases minus the income $C_{n,t}^{exp,P2P}$ from the sales, both in [€], as expressed in (5). The cost of the imported energy from CSC peers is given by (6) and the income from selling to other CSC peers in (7).

$$C_n^{P2P} = \sum_t^T C_{n,t}^{imp,P2P} - C_{n,t}^{exp,P2P} \tag{5}$$

$$C_{n,t}^{imp,P2P} = \lambda_{n,t}^{P2P} \cdot P_{n,t}^{imp,P2P} \cdot \Delta t \tag{6}$$

$$C_{n,t}^{exp,P2P} = \lambda_{n,t}^{P2P} \cdot P_{n,t}^{exp,P2P} \cdot \Delta t \tag{7}$$

where $P_{n,t}^{imp,P2P}$ and $P_{n,t}^{exp,P2P}$ are the powers bought and sold within the CSC in [kW] at the local electricity price $\lambda_{n,t}^{P2P}$ in [€/kWh], assumed all constant during Δt. This price was set as the mean value between the grid export and import prices [36], [37], [38], as in (8).

$$\lambda_{n,t}^{P2P} = \frac{\lambda_t^{imp,grid} + \lambda_t^{exp,grid}}{2} \tag{8}$$

The net power imported from the grid for each Δt and considering all the DERs belonging to the CSC (see Figure 3) is given in (9):

$$P_{n,t}^{imp,grid} = u_{n,t}^{imp,grid} \cdot \left(P_{n,t}^{grid} - \alpha_{n,t} \cdot P_t^{exc,tot}\right); \quad u_{n,t}^{imp,grid} = \{1(imp), 0(exp)\} \tag{9}$$

where $u_{n,t}^{imp,grid}$ is the grid import binary variable, $P_{n,t}^{grid}$ in [kW] is the power measured at each participant utility meter that results from the energy balance between each DER consumption, PV generation and battery operation as in (10), $\alpha_{n,t}$ is the AC defined for each

DER at the specific time step, $P_{n,t}^{exc}$ is the power surplus of each DER given in (11), and $P_t^{exc,tot}$ is the sum of all DERs power surpluses given in (12).

$$P_{n,t}^{grid} = P_{n,t}^{cons} - P_{n,t}^{gen} - P_{n,t}^{BT} \tag{10}$$

$$P_{n,t}^{exc} = \max\left(-P_{n,t}^{grid}, 0\right) \tag{11}$$

$$P_t^{exc,tot} = \sum_{n=1}^{N} P_{n,t}^{exc} \tag{12}$$

Similarly, the power exported to the grid given in (13) where $u_{n,t}^{exp,grid}$ is the grid export binary variable and $u_{n,t}^{exp,base}$ is the binary parameter for the ISC operation that results in a power export for each Δt, being the 1 for grid exports and 0 for imports.

$$P_{n,t}^{exp,grid} = u_{n,t}^{exp,grid} \cdot \left(\alpha_{n,t} \cdot P_t^{exc,tot} - \left(1 - u_{n,t}^{exp,base}\right) \cdot P_{n,t}^{grid}\right) \tag{13}$$

Local sales (that result from the ACs) and purchases are in (14) and (15) respectively, and must be balanced as in (16).

$$P_{n,t}^{imp,P2P} = \alpha_{n,t} \cdot P_t^{exc,tot} \tag{14}$$

$$P_{n,t}^{exp,P2P} = - \ u_{n,t}^{exp,base} \cdot P_{n,t}^{grid} \tag{15}$$

$$\sum_{n=1}^{N} P_{n,t}^{imp,P2P} = \sum_{n=1}^{N} P_{n,t}^{exp,P2P} \tag{16}$$

Constraint (17) avoids simultaneous power import from and export to the grid:

$$u_{n,t}^{imp,grid} + u_{n,t}^{exp,grid} \leq 1 \tag{17}$$

Some additional constraints to ensure robustness and feasibility are added. First, (18) guarantees that the energy component of the retailer’s bill for the billing period remains non-negative to comply with the self-consumption Spanish regulation. Second, (19) ensures that energy is only allocated when there are surpluses. For that, a binary parameter ($u_t^{exc,tot}$) is introduced when $P_t^{exc,tot}$ is higher than 0. Third, (20) ensures that in each time step the sum of all AC $\alpha_{n,t}$ is equal to 1.

$$\sum_{t=0}^{T}\left(\lambda_{n,t}^{imp,grid} \cdot P_{n,t}^{imp,grid} \cdot \Delta t - \lambda_{n,t}^{exp,grid} \cdot P_{n,t}^{exp,grid} \cdot \Delta t\right) \geq 0 \tag{18}$$

$$\alpha_{n,t} \leq u_t^{exc,tot} \tag{19}$$

$$\sum_{n=1}^{N} \alpha_{n,t} = u_t^{exc,tot} \tag{20}$$

Finally, (21) ensures that all participants benefit from belonging to the CSC, enforcing that their total energy bill when being part of the CSC is below their energy bill when operating as an ISC.

$$C_n^{retailer} + C_n^{P2P} \leq \sum_{t=0}^{T} \lambda_{n,t}^{imp,grid} \cdot P_{n,t}^{imp,grid,base} \cdot \Delta t - \lambda_{n,t}^{exp,grid} \cdot P_{n,t}^{exp,grid,base} \cdot \Delta t \tag{21}$$

2.2 Centralized EMS

In this section, only new variables are defined: for the rest refer to the previous section. The proposed centralized EMS is formulated as a mixed-integer nonlinear programming (MINLP) problem. The objective function, (22), minimizes the total operating costs:

$$\min \sum_{n=1}^{N}\left(\sum_{t=0}^{T}\left(P_{n,t}^{imp,grid} \cdot \Delta t \cdot \lambda_{n,t}^{imp,grid} - P_{n,t}^{exp,grid} \cdot \Delta t \cdot \lambda_{n,t}^{exp,grid}\right)\right) \tag{22}$$

To ensure consistency in P2P trades, (23) enforces these transactions to be reciprocal:

$$P_{n,m,t}^{imp,P2P} = P_{m,n,t}^{exp,P2P} \tag{23}$$

where $P_{n,m,t}^{imp,P2P}$ is the power bought by n from m and $P_{n,t}^{exp,P2P}$ is the power sold by m to n. Regarding energy allocation, fixed and proportional-to-consumption ACs are considered. The values of the fixed ACs, defined during the licensing period, are derived as described in the previous section. Thus, when using fixed ACs, the power that a consuming member n ($P_{n,t}^{grid} \geq 0$) can purchase from a producing member m ($P_{m,t}^{grid} < 0$) is determined by (24):

$$\begin{cases} P_{n,m,t}^{imp,P2P} = \alpha_{n,t}^{adj} \cdot P_{m,t}^{exc}, & if\ P_{n,t}^{grid} \geq 0 \land P_{m,t}^{grid} < 0 \\ P_{n,m,t}^{imp,P2P} = 0, & if\ P_{n,t}^{grid} < 0 \lor P_{m,t}^{grid} \geq 0 \end{cases} \tag{24}$$

where $\alpha_{n,t}^{adj}$ is the normalized AC. This AC normalization, applied in the Portuguese regulation, redistributes the local surplus only among consuming members based on their ex-ante ACs, and excludes the producing members so that the total sum of $\alpha_{n,t}^{adj}$ remains 1. These normalized ACs, $\alpha_{n,t}^{adj}$, are computed as in (25):

$$\alpha_{n,t}^{adj} = \frac{\alpha_{n,t}}{\sum_{k \in \left\{P_{k,t}^{grid} > 0\right\}} \alpha_{k,t}} \tag{25}$$

where $\alpha_{n,t}$ is the ex-ante AC. Meanwhile, when using proportional ACs, the ex-ante ACs are no longer required. Instead, the power a consuming member n purchases from a producing member m is computed according to (26):

$$\begin{cases} P_{n,m,t}^{imp,P2P} = \alpha_{n,t} \cdot P_{m,t}^{exc}, & if\ P_{n,t}^{grid} \geq 0 \land P_{m,t}^{grid} < 0 \\ P_{n,m,t}^{imp,P2P} = 0, & if\ P_{n,t}^{grid} < 0 \lor P_{m,t}^{grid} \geq 0 \end{cases} \tag{26}$$

where $\alpha_{n,t}$ is the proportional AC calculated based on the net consumption of each member, as in (27):

$$\alpha_{n,t} = \frac{P_{n,t}^{grid}}{\sum_{k\in\left\{P_{k,t}^{grid}>0\right\}} P_{k,t}^{grid}} \tag{27}$$

Proportional ACs ensure that local production is allocated exclusively to members who are consuming and distributed proportionally to their consumption. This approach minimizes the surplus not shared locally and allocate more energy to the members with higher consumption. Next, the energy trade balance is given by (28):

$$P_{n,t}^{grid} = P_{n,t}^{imp,grid} - P_{n,t}^{exp,grid} + \sum_{m=1,m\neq n}^{M} \left(P_{n,m,t}^{imp,P2P} - P_{n,m,t}^{exp,P2P}\right) \tag{28}$$

The energy balance accounts for consumption, behind-the-meter PV generation, and the operation of the ESS, and is given by (29):

$$P_{n,t}^{grid} = P_{n,t}^{cons} - P_{n,t}^{gen} + \sum_{s=1}^{S} \left(P_{n,s,t}^{BT,chg} - P_{n,s,t}^{BT,dch}\right) \tag{29}$$

where and $P_{n,s,t}^{BT,chg}$ and $P_{n,s,t}^{BT,dch}$ are, respectively, the power charged and discharged by each ESS. Next, (30) limits the members' power exchanges to their contracted power $P_{n}^{contracted}$:

$$-P_{n}^{contracted} \leq P_{n,t}^{grid} \leq P_{n}^{contracted} \tag{30}$$

Regarding the ESS, their energy is tracked with (31):

$$E_{n,s,t}^{ESS} = E_{n,s,t-1}^{ESS} + \left(P_{n,s,t}^{BT,chg} \cdot \eta_{n,s}^{ESS,chg} - \frac{P_{n,s,t}^{BT,dch}}{\eta_{n,s}^{ESS,dch}}\right) \cdot \Delta t \tag{31}$$

where $E_{n,s,t}^{ESS}$ is the energy stored by the ESS, $E_{n,s,t-1}^{ESS}$ is the energy stored by the ESS in the previous time step, and $\eta_{n,s}^{ESS,chg}$ and $\eta_{n,s}^{ESS,dch}$ are its charging and discharging efficiencies, respectively. The SOC of each ESS is given by (32):

$$SOC_{n,s,t}^{B} = \frac{E_{n,s,t}^{ESS}}{E_{n,s}^{ESS,nom}} \cdot 100 \tag{32}$$

where $SOC_{n,s,t}^{B}$ is the SOC of the ESS, and $E_{n,s}^{ESS,nom}$ is its nominal capacity. Constraint (33) limits the SOC to minimum and maximum values, $SOC_{n,s}^{min}$ and $SOC_{n,s}^{max}$, respectively.

$$SOC_{n,s}^{min} \leq SOC_{n,s,t}^{B} \leq SOC_{n,s}^{max} \tag{33}$$

And ESS charging and discharging rates are limited by (34) and (35):

$$P_{n,s,t}^{BT,chg} \leq P_{n,s}^{BT,max} \tag{34}$$

$$P_{n,s,t}^{BT,dch} \leq P_{n,s}^{BT,max} \tag{35}$$

where $P_{n}^{BT,max}$ is the maximum charging and discharging power of the ESS. Finally, the energy component of the retailer's billing is constrained to remain non-negative to comply with the self-consumption Spanish regulation, as in (36).

$$\sum_{t=0}^{T} \left(P_{n,t}^{imp,grid} \cdot \Delta t \cdot \lambda_{n,t}^{imp,grid} - P_{n,t}^{exp,grid} \cdot \Delta t \cdot \lambda_{n,t}^{exp,grid} \right) \geq 0 \tag{36}$$

2.3 Decentralized EMS

The decentralized EMS developed in this work is a hierarchical rule-based approach whose main objective is the minimization of the individual daily operation costs. The decentralized EMS consists of a high-level strategy for the planning stage and a low-level strategy for real-time operation.

2.3.1 Decentralized EMS: high-level strategy

The high-level EMS strategy schedules the battery operation to reduce the DER grid-imported energy cost considering also CSC energy sharing, and is based on rules whose behaviour depend on the following variables: a) generation energy, b) consumption energy, c) grid import electricity price, d) grid export electricity price, e) CSC fixed ACs and f) CSC fixed ACs impacts.

The consumption share matrix ($M \in \mathbb{R}_{\geq 0}^{N \times T}$) reflects the consumption share of each CSC member consuming at time t, as shown in (37):

$$M_{n,t} = \begin{cases} \frac{P_{n,t}^{cons}}{\sum_{n=1}^{N} P_{n,t}^{cons}}, & if\ \alpha_{n,t} > 0 \\ 0, & if\ \alpha_{n,t} = 0 \end{cases} \tag{37}$$

The power bought locally by each member, as a result of applying the AC referred to its consumption, is given by matrix $S \in \mathbb{R}_{\geq 0}^{N \times T}$, as defined in (38):

$$S_{n,t} = \begin{cases} \frac{AC_{n,t} \cdot P_t^{exc,tot}}{P_{n,t}^{cons}}, & if\ \alpha_{n,t} > 0\ \wedge\ P_{n,t}^{cons} > 0 \\ 0, & if\ \alpha_{n,t} = 0\ \vee\ P_{n,t}^{cons} = 0 \end{cases} \tag{38}$$

Matrix $Tmax \in \{0,1\}^{N \times T}$ is used to identify the time step with the maximum AC value for each DER, as in (39):

$$Tmax_{n,t} = \begin{cases} 1, & if\ \alpha_{n,t} = \max\limits_{j=1,\dots,T} \alpha_{n,t} \\ 0, & if\ \alpha_{n,t} \neq \max\limits_{j=1,\dots,T} \alpha_{n,t} \end{cases} \tag{39}$$

This $Tmax_{n,t}$ allows to determine which member has to be prioritized by other CSC members and in which time step, in order to know when to increase the shared energy, i.e. the energy surpluses, without grid cost consideration.

Two binary matrices are also defined: a) $BM \in \{0,1\}^{N \times T}$, that identifies the CSC members whose consumption exceeds 50% of the total CSC consumption at time t, as in

(40), and b) $BS \in \{0,1\}^{N\times T}$, indicating that the allocated energy exceeds consumption, which is useful for ESS charging decisions, as in (41).

$$BM_{n,t} = \begin{cases} 1, & if\ M_{n,t} > 0.5\ \wedge\ \alpha_{n,t} > 0 \\ 0, & if\ M_{n,t} \leq 0.5 \vee\ \alpha_{n,t} = 0 \end{cases} \tag{40}$$

$$BS_{n,t} = \begin{cases} 1, & if\ S_{n,t} > 1 \wedge\ \alpha_{n,t} > 0 \\ 0, & if\ S_{n,t} \leq 1 \vee\ \alpha_{n,t} = 0 \end{cases} \tag{41}$$

The high-level EMS was designed to schedule the ESS to avoid grid consumption at high-electricity price periods ($\lambda_{n,t}^{grid,imp} \geq \overline{\lambda_{n}^{grid,imp}}$), based on [34]. First, the amount of energy needed from the ESS ($E_{n,t}^{need}$ in [kWh]) is given in (42) as a function of the forecasted energies $E_{n,t}^{gen}$ and $E_{n,t}^{cons}$ (generated and consumed) and the retailer price, where $\overline{\lambda_{n}^{grid,imp}}$ is the daily mean value of the grid energy import price in [€/kWh].

$$E_{n,t}^{need} = \begin{cases} E_{n,t}^{cons} - E_{n,t}^{gen}, & \lambda_{n,t}^{grid,imp} \geq \overline{\lambda_{n}^{grid,imp}} \wedge E_{n,t}^{cons} > E_{n,t}^{gen} \\ 0, & \lambda_{n,t}^{grid,imp} \leq \overline{\lambda_{n}^{grid,imp}} \wedge E_{n,t}^{cons} \leq E_{n,t}^{gen} \end{cases} \tag{42}$$

From this, the time steps T_{n}^{need} during which energy from the ESS is needed are identified using (43). The corresponding starting point is denoted by $t_{n,0}^{need}$ in (44), and the total energy needed over T_{n}^{need} is calculated in (45).

$$T_{n}^{need} = \left\{ t \in T \middle| E_{n,t}^{need} > 0 \right\} \tag{43}$$

$$t_{n,0}^{need} = \min(T_{n}^{need}) \tag{44}$$

$$E_{n,t}^{need,tot} = \min\left(E_{n}^{ESS,nom}, \sum_{t \in T_{n}^{need}} E_{n,t}^{need} \right) \tag{45}$$

The desired energy in the ESS ($E_{n,t}^{desired}$) is the energy needed to supply $E_{n,t}^{need,tot}$, which must be stored X hours before $t_{n,0}^{need}$, as shown in (46), to ensure that ESS charging is scheduled in advance of discharge.

$$E_{n,t}^{desired} = \begin{cases} E_{n,t}^{need,tot}, & if\ t \in \left\{ t_{n,0}^{need} - x \middle| x = 1, \dots, X \right\} \\ 0, & otherwise \end{cases} \tag{46}$$

The high-level EMS is described in the pseudo-code in Table A1 of the Appendix section. The operation is classified into different operational modes based on the power balance. For each time step t (one hour in this work), three branches are defined: a) negative power balance, indicating an energy surplus scenario, b) positive power balance, representing an energy consumption scenario and c) zero power balance, denoting a state of equilibrium between generation and consumption.

Mainly, at the individual maximum AC instances ($Tmax_{n^{in},t}$) the ESS charging is prioritized as long as the ESS SOC allows it and the $BM_{n,t}$ and $BS_{n,t}$ are activated, as this grid energy is assumed to be the allocated energy within the CSC energy sharing. Otherwise, in the other CSC members maximum AC instances ($Tmax_{n^{out},t}$) with active $BM_{n,t}$ value the ESS discharge is prioritized to maximize surplus distribution among CSC members while individual objectives are preserved ($E_{n,t}^{desired}$). A more detailed description is provided in the Appendix.

2.3.2 Decentralized Energy Management System: low-level strategy

The low-level strategy is to ensure the correct operation of the battery with real-time measurements of generation and consumption powers and the ESS state. Building upon the strategy described in [34], several adaptations have been introduced, in order to be conservative with the HL EMS scheduled ESS operation during real-time operation.

Two additional metrics have been calculated. First, the variance of real-time generation, denoted as $Var_{n,t}^{Pgen}$, is computed with (47) to quantify the deviation of the measured real-time generation ($P_{n,t}^{gen,rt}$) from the clustered generation profile used in the AC calculation ($P_{n,t}^{gen,clus}$). Given the geographical proximity of CSC participants, it is assumed that this variance also affects the power generation of all the CSC members and consequently the expected amount of energy to be shared among them.

$$Var_{n,t}^{Pgen} = \frac{P_{n,t}^{gen,rt} - P_{n,t}^{gen,clus}}{P_{n,t}^{gen,clus}} \tag{47}$$

A negative variance indicates lower generation than expected, resulting in reduced surplus energy for sharing. Conversely, a positive variance suggests higher generation and increased energy sharing potential. As a result, grid-based ESS charging operations are limited, since the high-level strategy is programmed to prioritize charging from the grid expecting energy allocated through the CSC. In a negative variance case, a charge will result in a non-optimal operation with an extra retailer energy cost.

In addition, to prevent unnecessary ESS discharges aimed at increasing surplus energy for members with high AC values but low consumption impact, a matrix $Cbt_{n,t} \in \mathbb{R}_{\geq 0}^{N\times T}$ was defined. This matrix captures the normalized impact of external consumption ($P_{j,t}^{cons,AC}$) on the nominal energy capacity of the ESS for each member n ($E_{n}^{ESS,nom}$), under the condition that energy sharing is expected (49). The term $P_{n,t}^{cons,AC}$ refers to the adjusted consumption profile resulting from energy sharing within the data clustering scenario, as defined in (48).

$$P_{n,t}^{cons,AC} = \begin{cases} P_{n,t}^{cons} - \alpha_{n,t} \cdot P_{n,t}^{exc,tot}, & if \sum_{n \in N} \alpha_{n,t} > 0 \\ 0, & if \sum_{n \in N} \alpha_{n,t} > 0 \end{cases} \tag{48}$$

$$Cbt_{n,t} = \begin{cases} \dfrac{\sum_{j \in N, j \neq n} P_{j,t}^{cons,AC} \cdot \Delta t}{E_n^{ESS,nom}}, & if \sum_{n \in N} AC_{n,t} > 0 \\ 0, & if \sum_{n \in N} AC_{n,t} = 0 \end{cases} \tag{49}$$

The decentralized rule-based low-level strategy follows the logic of the high-level strategy, and operates using real-time generation, consumption and ESS powers. Additional conditions are incorporated to regulate ESS charging from the grid and prevent unnecessary grid consumption extra costs. Further details are provided in the Appendix Section.

2.4 Settlement and billing process

Finally, in the settlement stage, the final energy bill of the CSC is computed. This stage is divided in three parts: a) bill calculation, b) P2P evaluation and c) proportional ACs calculation. The energy bill calculation is done for each DER in the CSC and aggregated at CSC level, as expressed in (50) and (51) respectively, considering that the response error and times of the subsystems to the EMS setpoints are negligible. The graphical representation of the settlement process is depicted in Figure 2. For simplicity, only the energy term of the bill is computed. However, a complete electricity bill would also incorporate the contracted power term for each DER, the corresponding access tariffs and charges, and applicable electricity taxes.

$$Cost_{CSC}^{energy} = \sum_{n=1}^{N} Cost_{n}^{energy} \tag{50}$$

$$Cost_{n}^{energy} = \sum_{t=0}^{T} \left(C_{n,t}^{imp,grid} + C_{n,t}^{imp,P2P} - C_{n,t}^{exp,grid} - C_{n,t}^{exp,P2P} \right) \tag{51}$$

The ACs definition in the licensing period leads to non-optimal energy sharing among the CSC participants during operation due to the use of DERs' operation representative historical data and their discrepancy with real measurements. Therefore, it becomes necessary to evaluate the P2P energy sharing under real operating conditions and consider the recalculation of ACs based on updated generation and consumption data. This enables a more responsive and equitable energy sharing mechanism that better reflects the operational reality of the system.

The proportional ACs recalculation is done in the post-delivery period, once the energy is delivered. At each time step, the total surplus is first determined as the aggregated net export from all generating members. This available surplus is then allocated following a hierarchical approach. First, consuming DERs are prioritized by covering their demand until either their consumption is satisfied, or the aggregated surplus is exhausted. If any surplus remains, it is distributed among the generating DERs proportionally to their contributions to the total surplus.

Additionally, for each time step and participant, the settlement process identifies those cases where the original AC is zero and a surplus exists. In such cases, the surplus energy is proportionally redistributed among participants according to their individual contributions to the total surplus. Finally, the assigned values are normalized to obtain the new ACs, ensuring that their sum equals unity in every time step. This algorithm guarantees a fair and transparent redistribution of energy flows, since each participant's allocation reflects their actual role in both consumption and generation within the CSC scheme.

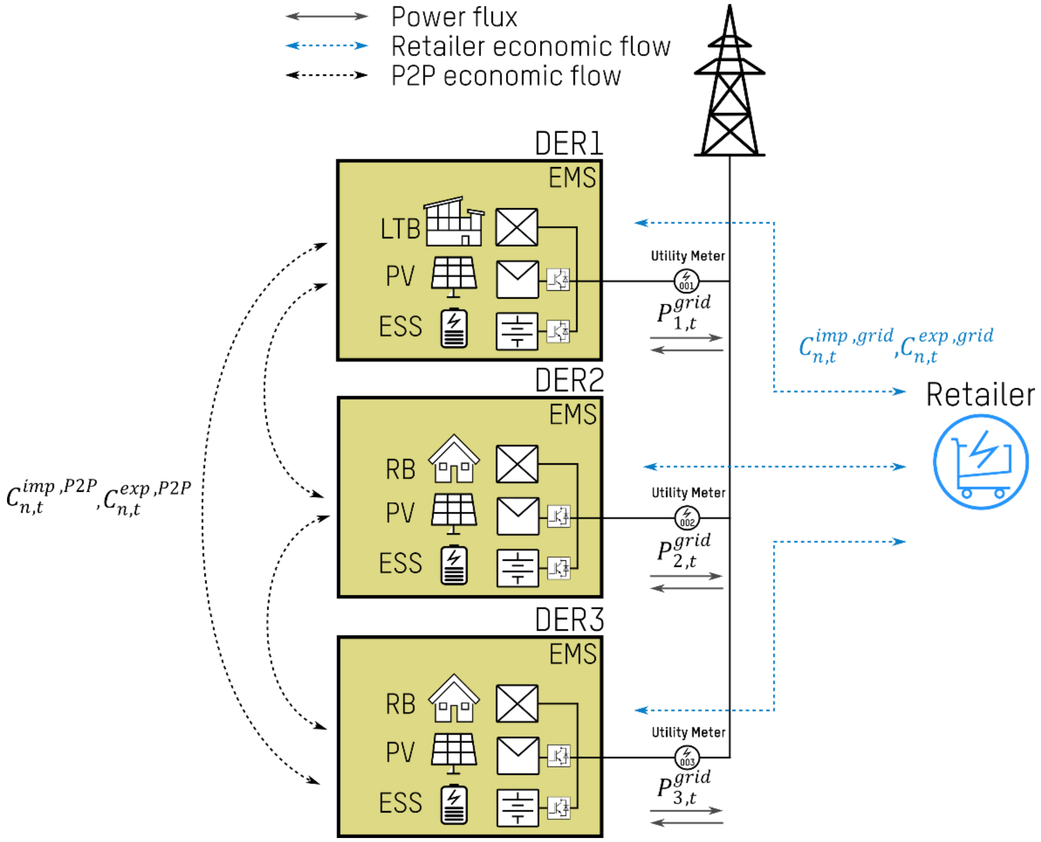

Figure 2: Graphical representation of the settlement process.

3. Collective Self-Consumption case study

3.1 Case study description

The proposed outline for the evaluation of the decentralised and centralised EMSs approaches for CSC within the Spanish regulatory framework is depicted in Figure 3. As introduced in Section 1, some regulatory adjustments based on the current Portuguese regulatory framework have been implemented to better support CSC schemes. These adjustments are in line with the new Spanish Royal Decree draft proposal (currently pending approval), which incorporates rules already adopted under Portuguese regulation, namely: a) the CSC AC calculation after the ISC scheme operation (contemplated in the draft), b) the possibility of internal P2P trades for the shared energy to increase profitability (not contemplated) and c) non-optimal AC correction in the billing period with proportional ACs (not contemplated).

The outline is divided into different blocks and timeframes. First, during the licensing or planning, the scenario and ex-ante ACs definition are executed (Section 2.1). Afterwards, in the operation, the DERs' EMS are performed (Sections 2.2 and 2.3), and finally, after energy delivery, the settlement is done for the corresponding billing period (Section 2.4).

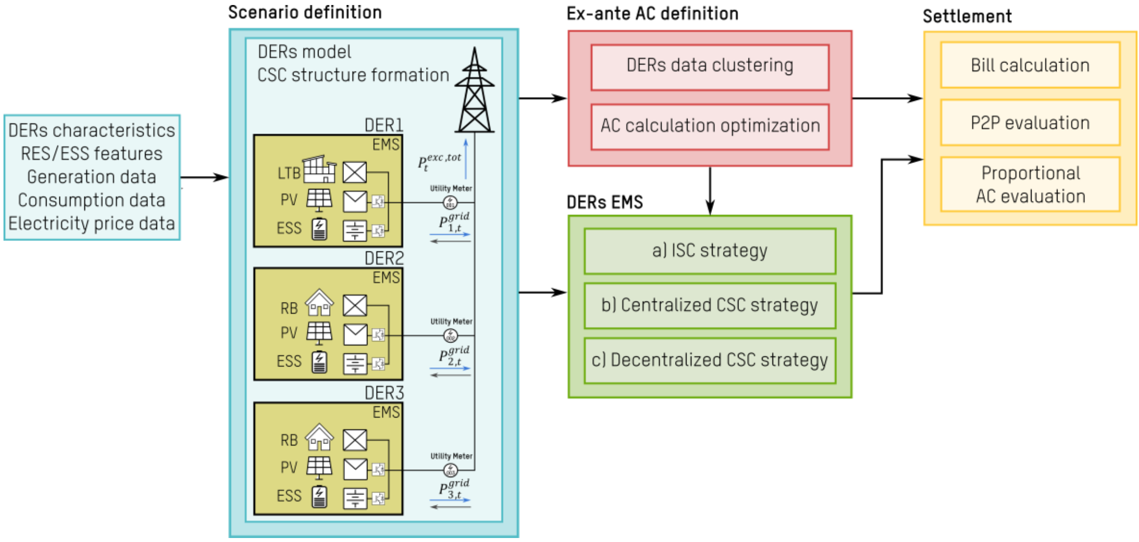

Figure 3: Case Study main diagram.

3.2 *Scenario definition*

The selected CSC scenario is composed of 3 DERs, one LTB and two RBs, as these ISC units are expected to be future participants engaged in CSC schemes. Specifically, this case study represents an unfavourable energy sharing configuration, as the chosen DERs exhibit a lack of complementarity. The objective is to assess whether performance improvements can still be achieved under these conditions. The technical specifications of the DERs are summarized in Table 2, including contracted power and annual energy consumption, installed PV capacity and annual energy generation, as well as ESS energy capacity and nominal voltage. The historical dataset used for this study corresponds to the year 2023, with annual mean values of 0.1468 €/kWh for imported energy and 0.08709 €/kWh for exported energy to the grid prices. The generation and consumption profiles are used without including any forecasting errors or predictive adjustments. All the ESS have the same SOC limits, with set to a minimum of 10% (SOC_n^{min}) and a maximum of 90% (SOC_n^{max}), and identical charging and discharging efficiency of 86.4% ($\eta_n^{ESS,chg} = \eta_n^{ESS,dch}$).

Table 2: Technical parameters of the DERs.

Member	**Consumption**		**PV installation**		**ESS**	
	Cont. power	**Annual energy**	**Power**	**Annual energy**	**Capacity**	**Voltage**
DER1 (LTB)	40 kW	142,887.20 kWh	32 kW	44,980.97 kWh	8.64 kWh	48 V
DER2 (RB)	4.0 kW	7,491.04 kWh	3.2 kW	4,498.09 kWh	2.04 kWh	24 V
DER3 (RB)	6.0 kW	12,793.43 kWh	4.8 kW	6,747.14 kWh	5.76 kWh	48 V

3.3 Energy management system strategies for distributed energy resources

Annual simulations are conducted during the operational phase to evaluate the three EMS strategies considered: a) ISC, b) Centralized CSC, and c) Decentralized CSC. The ISC algorithm described in Section 2.1 for the ACs calculation is used as the baseline EMS for each DER [34]. This predictive EMS is a rule-based algorithm composed of different modules designed to control an ESS within a self-consumption installation. In the first stage, the planning stage, the forecasting and high-level strategy modules are executed to define the daily optimal ESS operation schedule to minimize electricity costs and maximize self-sufficiency. Subsequently, during the operational stage, the low-level strategy module is executed to adjust operations based on real-time measurements.

The centralized EMS supervises the operation of all DERs within a CSC scheme. Its deployment requires an entity such as a CSC manager, who is responsible for managing all the DERs, as well as collecting and processing data. The centralized EMS has access to data from all the participating DERs. Having this full overview of the CSC scheme allows for a collective optimization that is expected to outperform local control strategies with respect to the defined objective function. Its detailed implementation has been presented in Section 2.2.

Lastly, the decentralized EMS is an adaptation of the ISC-oriented EMS, designed to operate independently within a CSC scheme without requiring real-time data from other DERs, thereby preserving user privacy. Instead, it incorporates certain impact indicators to adjust the local ESS control strategy. The detailed implementation of this decentralized EMS has been presented in Section 2.3. In this paper, a X value of 3 hours and a y parameter of 0.25 (a generation variance of 25 %) are implemented.

4. Techno-economic comparison of centralized and decentralized Energy Management Systems

The techno-economic analysis is divided into four parts. First, the three different EMSs (ISC, centralized CSC and decentralized CSC) are compared to evaluate their operation and ESS control decisions in terms of energy management. Then, a technical assessment evaluates the performance of the CSC schemes using several KPIs and compares them with the ISC scenario. Similarly, an economic assessment based on parameters such as energy cost savings compares all approaches. Lastly, the computational performance of the centralized and decentralized strategies is compared.

4.1 DERs' assets operation analysis

The DERs' assets operation analysis examines the behaviour of the DERs under each EMS strategy. The goal is to compare the different approaches in terms of the resulting energy balances, including grid and P2P exchanges, as well as ESS operation.

4.1.1 ISC strategy

The power profiles for DER1 under ISC, where DERs operate independently, are shown in Figure 4 for one selected day. Negative (resp. positive) battery power profile values indicate the ESS is being charged (resp. discharged).

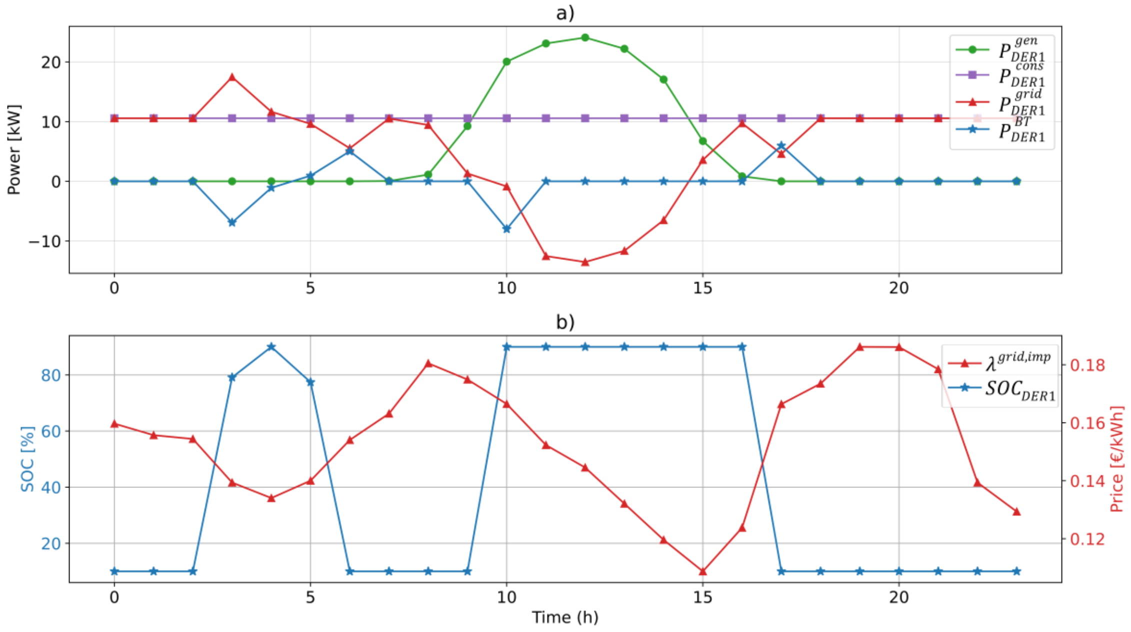

Figure 4: ISC EMS – DER1; a) power profiles and b) SOC and grid import prices.

As can be seen, during the morning DER1 imports power from the grid to cover its consumption. As solar generation starts to increase, part of it is used to meet local demand, while the surplus is stored in the ESS. Around midday, when generation exceeds consumption and ESS capacity, the resulting surplus is exported to the grid. Then, as PV generation decreases, DER1 discharges its ESS to support local demand and reduce grid imports. Hence, without CSC, DER1 alternates between relying on the grid during low-generation periods with no energy in the ESS and on storing energy during high-generation hours, exporting the remaining surpluses to the grid.

4.1.2 Centralized CSC strategy

The power profiles for DER1 under the centralized EMS are shown in Figure 5 for fixed ACs and in Figure 6 for proportional ACs. Compared to ISC scenario, DERs participate in P2P trading, where positive values indicate P2P imports and negative values P2P exports. As observed, DER1 exhibits similar behaviour under both AC types. It starts by importing energy from the grid, and as PV generation increases, it is used to meet local demand, with surplus being stored in the ESS until it is fully charged. Afterwards, the remaining surplus is either sold to the other DERs or to the grid. Once PV generation is no longer available, the DERs rely on grid imports and ESS discharge. The ESS behaviour is comparable across both ACs; however, this does not imply identical operation. In both ACs, ESS is managed to minimize total costs, which depends on the cost allocation determined by the ACs. The similarity arises because all DERs have the same energy prices, making the cost allocation indifferent to the distribution of surplus among DERs. Consequently, the main differences between the two ACs types are observed in the P2P exchanges, with small shifts in their timing and magnitude. Moreover, under the centralized EMS, DERs do not receive energy from P2P imports during hours when they have an energy surplus, which is an outcome of the normalization of the fixed ACs, described in Section 2.2.

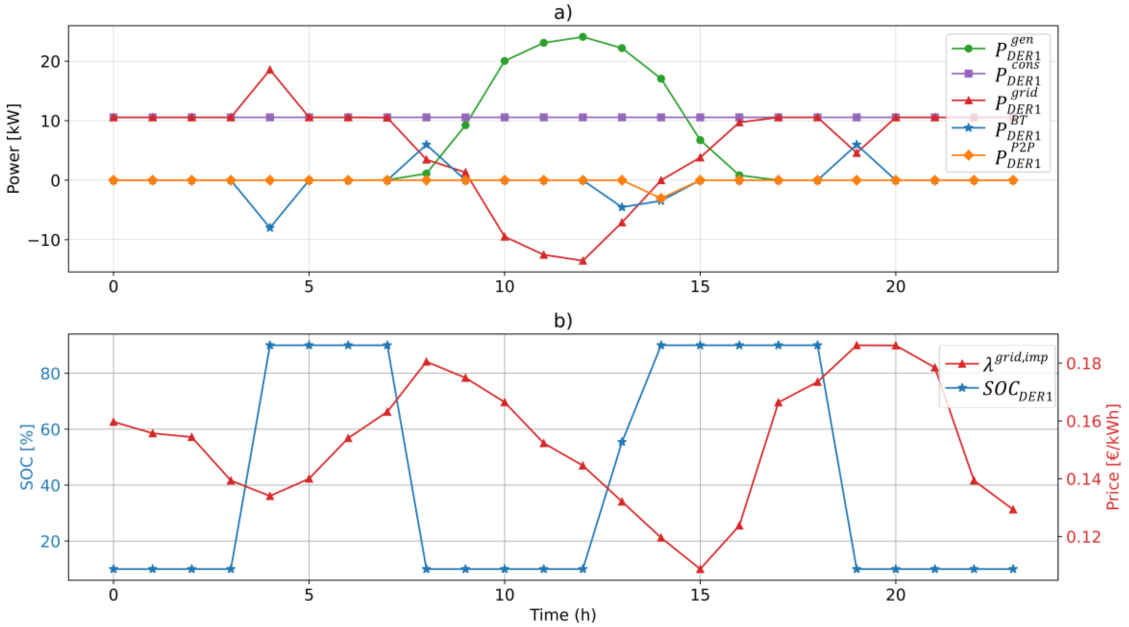

Figure 5: Centralized EMS – DER1 operation with fixed ACs; a) power profiles and b) SOC and grid import prices.

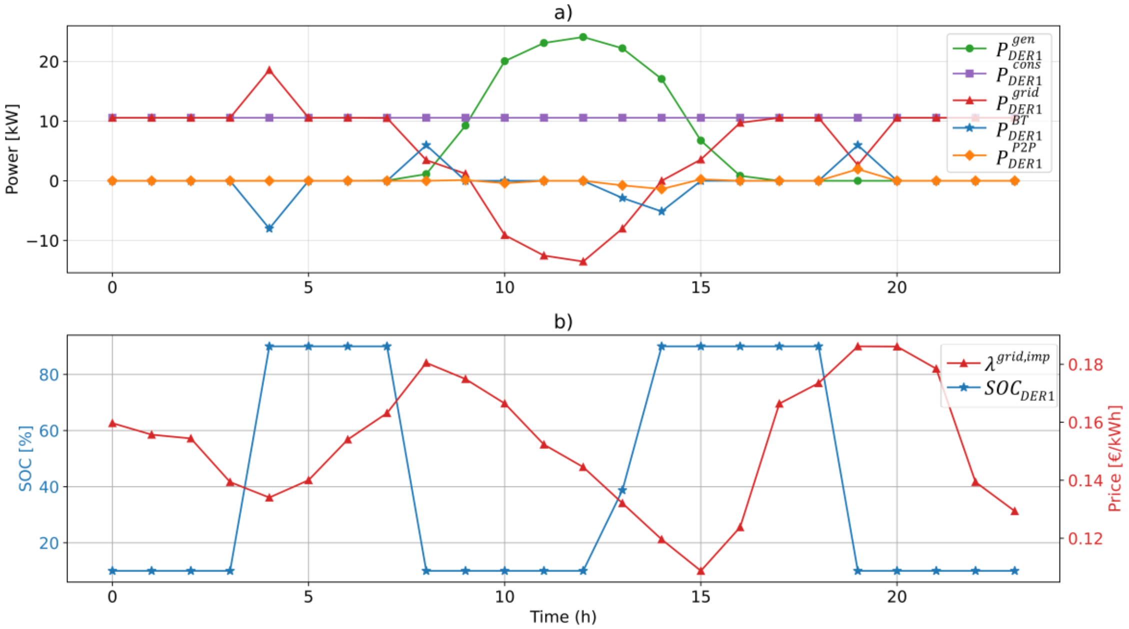

Figure 6: Centralized EMS – DER1 operation with proportional ACs; a) power profiles and b) SOC and grid import prices.

4.1.3 Decentralized CSC strategy

The power profiles for DER1 under the decentralized CSC EMS strategy are shown in Figure 7 for fixed ACs and in Figure 8 for proportional ACs. As in the centralized EMS, the overall ESS operation remains mostly similar across both ACs. Additionally, since the decentralised EMS uses the same rule-based logic for both ACs to operate the ESS, charging and discharging patterns are identical for both schemes. Therefore, the main differences are in P2P exchanges, with their timing and magnitude varying depending on the used ACs. Remarkably, under fixed ACs, DER1 receives energy from P2P imports during hours when it has a local surplus, for instance at 13h, highlighting the inefficiency and disadvantage of these ACs. Meanwhile, under proportional ACs, this situation does not arise, showing an advantage of the latter.

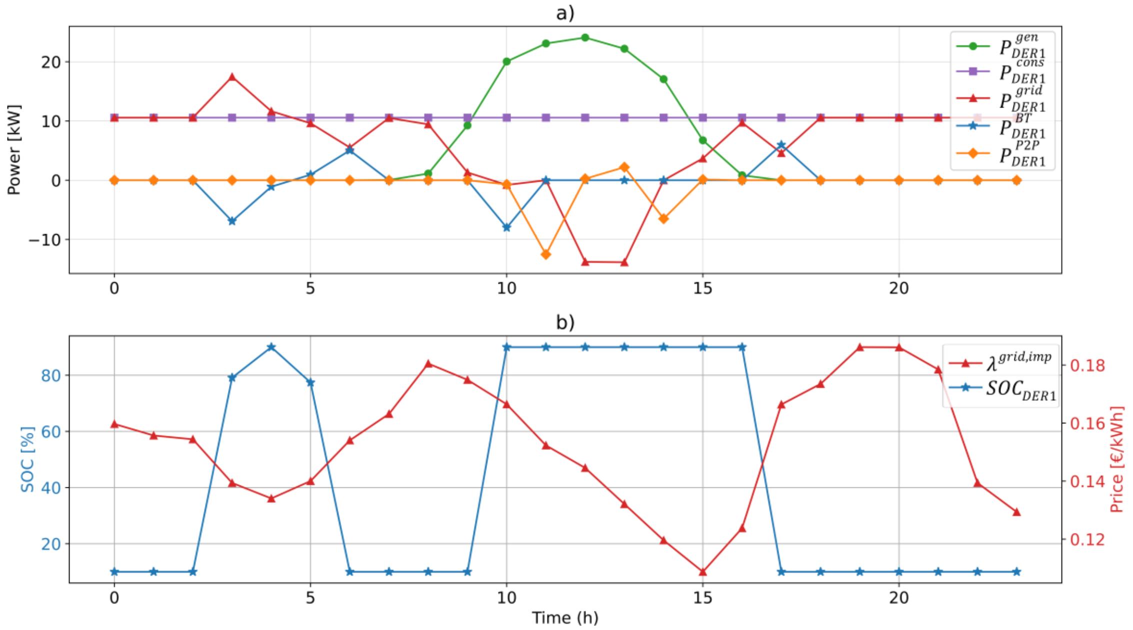

Figure 7: Decentralized EMS – DER1 operation with fixed ACs; a) power profiles and b) SOC and grid import prices.

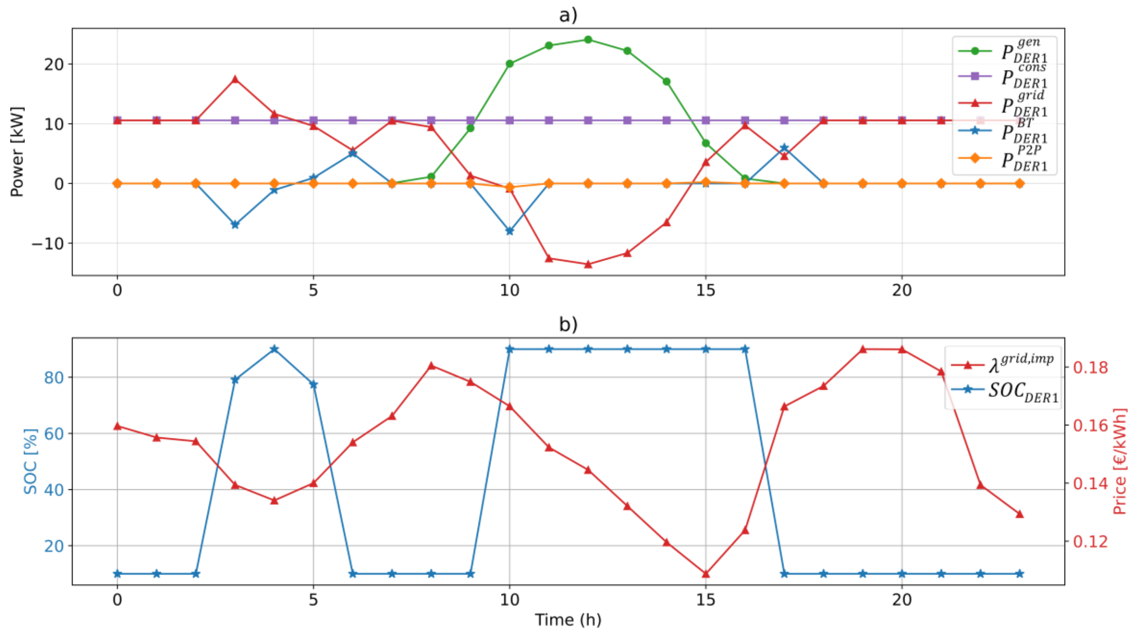

Figure 8: Decentralized EMS – DER1 operation with proportional ACs; a) power profiles and b) SOC and grid import prices.

4.2 Technical performance analysis

For the technical analysis a set of KPIs are calculated, including the self-consumption ratio (SCR), the self-sufficiency ratio (SSR), and the energy sharing ratio (ESR). The SCR is defined as the ratio between the self-consumed energy and the generated energy, representing self-generated energy utilization. The SSR is defined as the ratio between self-consumed energy and the total consumed energy, indicating grid independence. Different formulations are needed when applying these KPIs to ISC and to CSC. Finally, the ESR is defined as the ratio between the total energy shared among the DERs and the total generated energy.

The ISC SCR is calculated as expressed in (52), where $E_{n,t}^{gen,cons,ISC}$ in [kWh] is the cumulative self-consumed energy of all the members operating with the ISC EMS and $E_{n,t}^{gen}$ in [kWh] is the generated energy of all members during the timeline T. $E_{n,t}^{gen,cons,ISC}$ is disaggregated into the consumption supplied by the generation installation ($E_{n,t}^{PV\rightarrow cons}$ in

[kWh]) and the generation energy used to charge the ESS ($E_{n,t}^{PV\rightarrow ESS,chg}$ in [kWh]), as expressed in (53). The ISC SSR is calculated employing (54), where $E_{n,t}^{cons}$ in [kWh] is the consumed energy by all members during the horizon T.

$$SCR_{total}^{ISC} = \frac{\sum_n^N \sum_t^T E_{n,t}^{gen,cons,ISC}}{\sum_n^N \sum_t^T E_{n,t}^{gen}} \cdot 100 \tag{52}$$

$$E_{n,t}^{gen,cons,ISC} = E_{n,t}^{PV\rightarrow cons} + E_{n,t}^{PV\rightarrow ESS,chg} \tag{53}$$

$$SSR_{total}^{ISC} = \frac{\sum_n^N \sum_t^T E_{n,t}^{gen,cons,ISC}}{\sum_n^N \sum_t^T E_{n,t}^{cons}} \cdot 100 \tag{54}$$

The CSC SCR is calculated in the same way, as shown in (55). In this case, $E_{n,t}^{gen,cons,CSC}$ in [kWh] includes $E_{n,t}^{PV\rightarrow cons}$, $E_{n,t}^{PV\rightarrow ESS,chg}$ and the energy imported from the CSC used for consumption ($E_{n,t}^{imp,P2P\rightarrow cons}$ in [kWh]) and to charge the ESS ($E_{n,t}^{imp,P2P\rightarrow ESS,chg}$ in [kWh]), as in (56). Meanwhile, the SSR for the CSC scheme is calculated as shown in (57).

$$SCR_{total}^{CSC} = \frac{\sum_n^N \sum_t^T E_{n,t}^{gen,cons,CSC}}{\sum_n^N \sum_t^T E_{n,t}^{gen}} \cdot 100 \tag{55}$$

$$E_{n,t}^{gen,cons,CSC} = E_{n,t}^{PV\rightarrow cons} + E_{n,t}^{PV\rightarrow ESS,chg} + E_{n,t}^{imp,P2P\rightarrow cons} + E_{n,t}^{imp,P2P\rightarrow ESS,chg} \tag{56}$$

$$SSR_{total}^{CSC} = \frac{\sum_n^N \sum_t^T E_{n,t}^{gen,cons,CSC}}{\sum_n^N \sum_t^T E_{n,t}^{cons}} \cdot 100 \tag{57}$$

Finally, the CSC ESR is calculated as expressed in (58).

$$ESR_{total}^{CSC} = \frac{\sum_n^N \sum_t^T E_{n,t}^{imp,P2P}}{\sum_n^N \sum_t^T E_{n,t}^{gen}} \cdot 100 \tag{58}$$

Table 3 presents the quarterly and annual results of the SCR under the different strategies. Both CSC strategies outperform ISC, which yields a SCR of 84.32%. The highest SCR is achieved by the centralized EMS with proportional ACs, reaching 89.79%. This is followed by the centralized EMS with fixed ACs at 87.48%. The decentralized EMS presents lower values, with a SCR of 85.35% and 86.36% for fixed and proportional ACs. These results highlight the benefits of the centralized EMS to increase self-consumption, particularly under proportional ACs to minimize surpluses and maximize self-consumption.

Table 3: Quarterly and annual SCR results comparison.

Quarter	**ISC**	**Centralized EMS CSC**		**Decentralized EMS CSC**	
		Fixed AC	**Prop. AC**	**Fixed AC**	**Prop. AC**
Q1	87.78%	89.93%	93.48%	88.89%	89.93%
Q2	84.25%	88.25%	90.34%	86.09%	87.37%
Q3	77.55%	79.44%	81.44%	77.85%	78.47%
Q4	91.20%	96.02%	97.82%	91.86%	92.93%
Annual	84.32%	87.48%	89.79%	85.35%	86.36%

Additionally, a seasonal pattern is observed in all strategies, where the SCR is lower in Q3 (summer) and higher in Q4 (autumn). In Q3, lower consumption combined with higher PV generation leads to greater injection into the grid and, consequently, a lower SCR. Meanwhile, in Q4, higher consumption and lower PV generation lead to more energy consumed locally, increasing the SCR.

Next, Table 4 presents the quarterly and annual results of the SSR under the different strategies. Again, both CSC strategies outperform ISC, which yields a SSR of 29.06%, and the highest SSR is achieved with the centralized EMS using proportional ACs, at 30.94%. This is followed by the centralized EMS with fixed ACs with 30.14%. The decentralized EMS presents slightly lower results, at 29.41% and 29.76% for fixed and proportional ACs, respectively. The same seasonal pattern is observed in all strategies, with the highest values being observed in Q3 due to a higher PV generation that reduces grid reliance, and the lowest values in Q4 when lower generation and higher consumption increase grid reliance.

Table 4: Quarterly and annual SSR results comparison.

Quarter	**ISC**	**Centralized EMS CSC**		**Decentralized EMS CSC**	
		Fixed AC	**Prop. AC**	**Fixed AC**	**Prop. AC**
Q1	23.70%	24.28%	25.24%	24.00%	24.28%
Q2	35.96%	37.66%	38.55%	36.74%	37.29%
Q3	37.57%	38.48%	39.45%	37.71%	38.01%
Q4	21.06%	22.34%	22.76%	21.37%	21.37%
Annual	29.06%	30.14%	30.94%	29.41%	29.76%

At last, Table 5 presents the quarterly and annual results of the ESR under the different strategies. Since ESR can only be computed when P2P trading is available, the values for ISC are set to 0%. The highest annual ESR is achieved under the centralized EMS with proportional ACs, reaching 7.32%, indicating this is the most effective regarding energy sharing between DERs. The second highest value corresponds to the decentralized EMS with fixed ACs, at 6.00%. The remaining strategies lead to lower ESR values, with the centralized EMS with fixed ACs at 3.71%, and the decentralized EMS with proportional ACs at 2.20%.

Table 5: Quarterly and annual ESR results comparison.

Quarter	**ISC**	**Centralized EMS CSC**		**Decentralized EMS CSC**	
		Fixed AC	**Prop. AC**	**Fixed AC**	**Prop. AC**
Q1	0.00%	3.78%	7.94%	6.18%	2.11%
Q2	0.00%	4.24%	7.68%	5.85%	3.14%
Q3	0.00%	2.29%	5.26%	7.58%	1.22%
Q4	0.00%	4.95%	9.24%	3.55%	2.21%
Annual	0.00%	3.71%	7.32%	6.00%	2.20%

The decrease in ESR in the decentralized EMS with proportional ACs compared to fixed ACs is primarily due to the decentralized structure itself. In this approach, proportional ACs are determined after energy delivery and are adjusted according to the actual consumption. This results in operating conditions where CSC members reduce their energy share based on real-time demand. In other words, the energy allocation is optimized according to real-time requirements, and any non-shared energy surplus is exported to the grid by its generator. Conversely, in the centralized EMS approach, proportional ACs are recalculated within the optimization process, enabling DER operation to maximize the energy sharing based on real-time asset values. Additionally, the difference in the ESR between the two EMSs under fixed ACs can be attributed to the objective of the decentralized EMS, where the ESS scheduling is designed to maximize energy sharing.

4.3 Economic performance analysis

The economic analysis evaluates the reduction in energy bills under CSC relative to ISC, and it is supported by the calculation of individual savings (IS) and collective savings (CS). The IS in [%] is calculated as the difference between the energy cost under CSC ($Cost_n^{energy,CSC-EMS}$ in [€]) and under ISC ($Cost_n^{energy,ISC-EMS}$ in [€]), with respect to the ISC energy cost, as in (59). Individual energy costs ($Cost_n^{energy}$) are calculated using (51).

$$IS_{total}^{CSC} = \frac{Cost_n^{energy,CSC-EMS} - Cost_n^{energy,ISC-EMS}}{Cost_n^{energy,ISC-EMS}} \cdot 100 \tag{59}$$

The CS in [%] is calculated as the difference between the total energy costs under CSC and the total costs under ISC, divided by the total costs under ISC, as in (60).

$$CS_{total}^{CSC} = \frac{\sum_n^N \left(Cost_n^{energy,CSC-EMS} - Cost_n^{energy,ISC-EMS}\right)}{\sum_n^N Cost_n^{energy,ISC-EMS}} \cdot 100 \tag{60}$$

Figure 9 depicts the quarterly energy costs within the simulated EMS strategies.

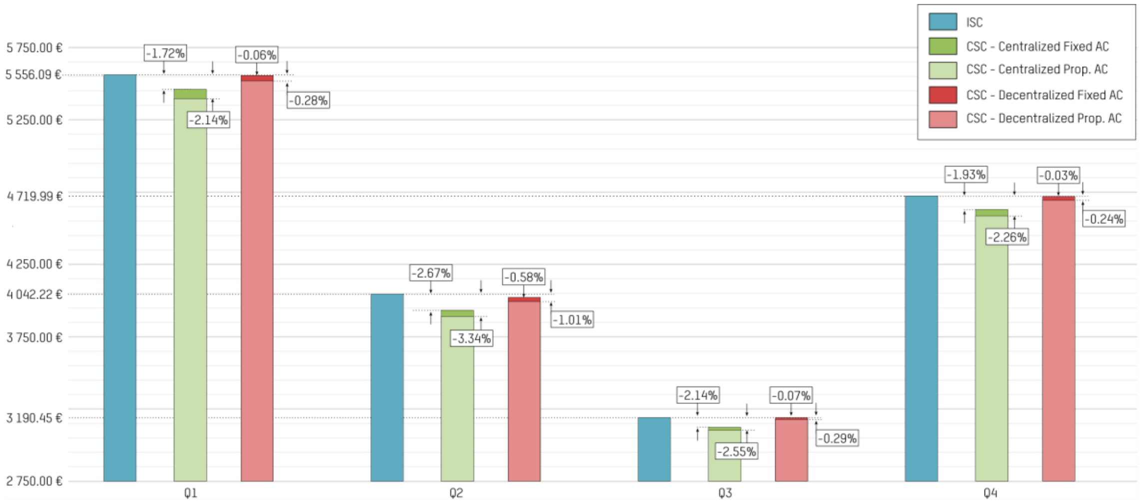

Figure 9: Quarterly energy costs and CS comparison of ISC and CSC schemes within centralized and decentralized EMS.

The centralized EMS with proportional ACs consistently achieves the highest savings across all quarters, while the decentralized EMS with fixed ACs leads to the lowest savings. Additionally, the best performance of the centralized EMS is recorded in Q2 using proportional ACs, with a CS of 3.34% (an average electricity price of 0.09432 €/kWh). This trend persists throughout the year, with proportional ACs consistently providing greater savings than fixed ACs, and the centralized EMS outperforming the decentralized EMS in costs minimization. Next, Table 6 presents the individual costs across all EMSs.

Table 6: Annual energy costs comparison between CSC members.

Member	**ISC**	**Centralized EMS CSC**		**Decentralized EMS CSC**	
		Fixed AC	**Prop. AC**	**Fixed AC**	**Prop. AC**
DER1	15 955.74 €	15 680.52 €	15 591.54 €	15 901.90 €	15 917.95 €
DER2	490.62 €	469.59 €	468.64 €	506.84 €	471.95 €
DER3	1 062.39 €	995.85 €	1 006.91 €	1 069.72 €	1 041.74 €
Annual	17 508.75 €	17 145.96 €	17 067.09 €	17 478.45 €	17 431.65 €

As expected, transitioning from ISC to CSC brings benefits in terms of individual costs. However, a more detailed analysis of each DER's costs reveals that not all members benefit equally from CSC. For instance, under the decentralized EMS with fixed ACs, DER1 reduces its costs from 15 955.74 € to 15901.90 €, whereas the costs for DER2 and DER3 increase. The main reason for this is the impact of the AC calculation during the licensing period. Since real-time operations are not considered, this results in suboptimal energy allocation (e.g., DER1 sells more energy to DER2 and DER3 than they need). Consequently, energy allocation based on proportional ACs proves to be the best approach, as it consistently delivers lower costs than fixed ACs. In this context, under the proportional AC operation, the centralized EMS achieves an annual collective reduction of 2.10% compared to the decentralized EMS operation.

4.3.1 Computational performance

The computational performance is evaluated by comparing the execution times of the centralized and decentralized EMSs, highlighting the trade-off between solution optimality and computational burden. All simulations were executed on a 64-bit Windows 11 workstation equipped with a processor (1.70 GHz) and 32 GB of RAM, and all developed algorithms were implemented in Python.

The data clustering function has been developed using the k-medoids and the sklearn libraries, and consequently, the fixed ACs calculation optimization has been developed using the Pyomo library with the Gurobi solver [40]. The centralized EMS, modelled as a MINLP, has been implemented using the Pyomo optimization library and solved using SCIP [41]. Regarding the rule-based decentralized EMS, it has been deployed using NumPy and Pandas libraries. All optimizations have been run daily over a 24-hour time horizon. The computational performance results are summarized in Table 7.

Table 7: Computational performance analysis results.

Runtimes	**ISC**	**Centralized EMS CSC**		**Decentralized EMS CSC**	
		Fixed AC	**Prop. AC**	**Fixed AC**	**Prop. AC**
Avg. monthly	3.39 s	14.20 s	66.35 s	3.62 s	3.62 s
Max. monthly	3.73 s	15.71 s	91.12 s	4.26 s	4.26 s
Min monthly	3.18 s	12.98 s	46.08 s	3.25 s	3.25 s
Total (1 year)	40.67 s	170.44 s	796.27 s	43.51 s	43.51 s

The results show the decentralized EMS has a greater degree of scalability, making this approach suitable for larger CSC schemes, where a centralized EMS would be more computationally demanding, particularly under proportional ACs. Additionally, from an operational perspective, the low runtimes of the decentralized EMS make it compatible with real-time or near-real-time operation, while the centralized EMS might struggle as the number of CSC members or temporal resolution increase. Furthermore, the decentralized EMS offers easier short-term implementation, as it is simpler and does not require additional layers on top of the ISC EMS. In this way, it serves as an intermediate approach between ISC and the optimal CSC solution, as introducing a set of decentralized adjustments to the ISC EMS enables the system to progressively transition towards CSC while improving performance. The centralized EMS requires additional communication and control layers, as it is a global optimal solution. Thus, it is more costly and complex in terms of deployment, and this centralized controllability also entails extra service-related costs.

5. Conclusions

This paper has presented a techno-economic assessment of two EMS approaches for CSC within the Spanish regulatory framework. To improve performance and participation, several regulatory measures inspired by the Portuguese regulatory framework have been incorporated: a) the calculation of CSC ACs after the baseline operation of the ISC scheme, b) the inclusion of P2P energy trading for shared energy to increase profitability, and c) the proportional correction of ACs within the billing period to mitigate non-optimal allocations arising from fixed ACs computed ex-ante without being updated using real-time measurements.

The adoption of ISC DERs has been extended to CSC schemes, enabling operation under both fixed and proportional AC configurations (pre- and post-delivery ACs, respectively). The fixed ACs calculated in the licensing period have been determined through data clustering of historical consumption and generation profiles, and a centralized MILP optimization algorithm has been applied to support this process. Subsequently, two EMS architectures, a centralized optimization-based EMS and a decentralized rule-based EMS, have been designed and implemented for CSC schemes, enabling comparative evaluation under both fixed and proportional ACs.

The results have shown that, despite some differences, both EMSs lead to comparable energetic behaviours, with the centralized EMS being more adaptable, particularly under proportional ACs. Grid and P2P exchanges have followed comparable trends across, with some variations arising from the ACs methodology. Meanwhile, the technical KPIs evaluated have shown small differences between strategies. The centralized EMS with proportional ACs achieved the highest values, with a SCR of 89.79%, a SSR of 30.94%, and an ESR of 7.32%, an increase of 5.47% in SCR and 1.88% in SSR compared to the ISC case. Meanwhile, the decentralized EMS still outperformed ISC, achieving its highest SCR (86.36%) and SSR (29.76%) under proportional ACs, and the highest ESR (6.00%) under fixed ACs.

The economic KPIs also revealed differences between the simulated strategies. The centralized EMS delivered the highest cost reductions under proportional ACs, with a reduction of 2.52% compared to ISC, proving its ability to allocate energy more efficiently. The decentralized EMS also reduced costs, but only by 0.17% under fixed ACs and by 0.44% under proportional ACs. Thus, both EMS approaches have demonstrated an increase in the profitability of energy sharing within CSC schemes, driven by the integration of P2P trading. These results have suggested that adopting an approach for calculating ACs closer to real-time operation can improve both economic and energy performance, even under scenarios characterized by low DER complementarity. This evidence has highlighted the potential benefits of dynamic allocation mechanisms and warrants further investigation into their integration within existing Spanish regulatory frameworks.

The main limitation of the centralized EMS is its higher computational demand. For one year, the centralized EMS requires 796.27 s under proportional ACs and 170.44 s under fixed ACs, making it up to eighteen times slower than the decentralized EMS, which has a runtime of 43.51 s. This makes the decentralized EMS more suitable for larger CSC schemes or applications requiring near-real-time operation, while preserving data anonymity.

Finally, the findings have shown a clear trade-off between economic optimality and computational tractability. The decentralized EMS offers fast and scalable operation with performance close to that of the centralized EMS, while the centralized EMS provides superior cost minimization at the expense of higher computational effort, achieving a 2.10% reduction in the energy bill but operating up to eighteen times slower. The simplicity of the decentralized EMS facilitates the transition from ISC schemes to CSC, requiring fewer modifications compared to the centralized EMS. The latter provides optimal solutions, but it adds complexity and requires extra control and information layers. The results of this study support the development of new business models, with the decentralized EMS facilitates the adoption of CSC by ISC consumers, as it requires fewer modifications to existing infrastructure and allows for simpler short-term implementation. Consequently, this approach is more practical in contexts characterized by dynamic or evolving regulatory frameworks.

Nevertheless, the scope of this work is limited to a specific case study and regulatory framework. In scenarios with a larger number of participants and a higher diversity of DERs, beyond the current configuration based on PV-based self-consumption and with heterogeneous consumption patterns, greater complementarity among consumption and generation profiles could be expected. Such diversity along with more flexible regulations would enable higher levels of energy sharing and enhanced economic and energy performance for both EMS approaches.

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Appendix

The pseudo-code of the decentralized high-level EMS is presented in Table A1. The high-level EMS is divided into different operational modes based on the power balance computed in line 2. As described in Section 2.3, for each time step t (one hour in this work), three branches are defined: a) negative power balance, indicating an energy surplus scenario (lines 8-21), b) positive power balance, representing an energy consumption scenario (lines 22-27) and c) zero power balance, denoting a state of equilibrium between generation and consumption (lines 28-37).

In the energy surplus scenario, at the individual maximum AC instances ($Tmax_{n^{in},t}$ in line 9) the ESS charging is prioritized as long as the ESS SOC allows it. The charged energy will come from PV generation or the grid, as this grid energy is assumed to be the allocated energy within the CSC energy sharing (lines 10 and 11). Subsequently, in the other CSC members maximum AC instances ($Tmax_{n^{out},t}$) with active $BM_{n,t}$ value, the ESS discharge is prioritized to maximize surplus distribution among CSC members while individual objectives are preserved ($E_{n,t}^{desired}$) in lines 13-15.

In the case of not having enough generation to meet consumption demand, ESS charging is scheduled only if individual $Tmax_{n,t}$, $BM_{n,t}$ and $BS_{n,t}$ are activated during low electricity price periods (lines 22-25). In the final scenario, where the generation covers the exact amount of the consumption power, as in the two previous cases, the ESS charge from the grid is prioritized in individual $Tmax_{n,t}$ and $BM_{n,t}$ instances, expecting CSC energy sharing (lines 28-31). Furthermore, the ESS is partially discharged due to $E_{n,t}^{desired}$ when other CSC members $Tmax_{n,t}$, $BM_{n,t}$ are activated (line 33). If none of the aforementioned conditions were met, the EMS operates under standard conditions following the ISC strategy outlined in [34] (lines 21, 27 and 35).

All the chargeable and dischargeable power rates and the ESS energy levels have been calculated at the beginning of each time step (lines from 4 to 7). In line 4, the actual ESS energy was calculated, with $E_n^{ESS,nom}$, the SOC_n^{ini} is the ESS SOC in [%] at the simulation initial point ($t = 1$), $E_{n,t-1}^{ESS}$ is the energy stored in the previous time step (in [kWh]) and $P_{n,t-1}^{BT}$ is the power provided by the ESS during the previous time step (Δt in [h]). In line 5, the available energy in the ESS was calculated ($E_{n,t}^{available,ESS}$) in [kWh]), where $\eta_n^{ESS,dch}$ is the ESS discharge efficiency in [%]. In line 6, the chargeable energy of the ESS was calculated ($E_{n,t}^{chargeable,ESS}$) in [kWh]), where $\eta_n^{ESS,chg}$ is the charge efficiency of the ESS in [%]. Finally, power limit constraints were applied in line 38, ensuring that the grid power calculated via (10) did not exceed the contracted power for each CSC member.

Table A1: The decentralized HL EMS pseudo-code.

```
Pseudo-code: Decentralized rule-based high-level EMS
1: Calculate desired energy in the ESS (46)
2: Calculate power balance: $P_{n,t}^{balance} = P_{n,t}^{cons} - P_{n,t}^{gen}$
3: for t= 1 to T
4: Calculate ESS energy $E_{n,t}^{ESS} = \begin{cases} E_n^{ESS,nom} \cdot SOC_n^{ini}, \ if\ t = 1 \\ E_{n,t-1}^{ESS} - P_{n,t-1}^{BT} \cdot \Delta t, \ if\ t > 1 \end{cases}$
5: Calculate ESS available energy: $E_{n,t}^{available,ESS} = \left(E_{n,t}^{ESS} - E_n^{ESS,nom} \cdot SOC_n^{min}\right) \cdot \eta_n^{ESS,dch}$
6: Calculate ESS chargeable energy: $E_{n,t}^{chargeable,ESS} = \left(E_n^{ESS,nom} \cdot SOC_n^{max} - E_{n,t}^{ESS}\right) / \eta_n^{ESS,chg}$
7: Calculate ESS charge and discharge powers $P_{n,t}^{BT,chg} = \min\left(P_n^{BT,max}, E_{n,t}^{chargeable,ESS} / \Delta t\right)$; $P_{n,t}^{BT,dch} = \min\left(P_n^{BT,max}, E_{n,t}^{available,ESS} / \Delta t\right)$
8: if $P_{n,t}^{balance} < 0$
9: if $Tmax_{n^{in},t}$
10: if $E_{n,t}^{chargeable,ESS} > 0$ then Charge ESS surplus and grid; $P_{n,t}^{BT} = -P_{n,t}^{BT,chg}$
```

```
    11: else Standby ESS and surplus injected to grid; $P_{n,t}^{BT} = 0$
    12: end if (line 10)
    13: elseif $Tmax_{n^{out},t}$ and $BM_{n^{out},t}$
    14: if $E_{n,t}^{available,ESS} > E_{n,t}^{desired}$ then Discharge ESS until $E_{n,t}^{desired}$ ; $P_{n,t}^{BT} = \min\left(P_{n,t}^{BT,dch}, \left(E_{n,t}^{desired} - E_{n,t}^{available,ESS}\right)/\Delta t\right)$
    15: else Standby ESS and surplus injected to grid $P_{n,t}^{BT} = 0$
    16: end if (line 14)
    17: elseif $Tmax_{n^{out},t+1}$ and $BM_{n^{out},t+1}$
    18: if $E_{n,t}^{chargeable,ESS} > 0$ then Charge ESS surplus and grid $P_{n,t}^{BT} = -P_{n,t}^{BT,chg}$
    19: else Standby ESS and surplus injected to grid; $P_{n,t}^{BT} = 0$
    20: end if (line 18)
    21: else Normal operation (based on [34])
  22: elseif $P_{n,t}^{balance} > 0$
    23: if $Tmax_{n^{in},t}$ and $E_{n,t}^{chargeable,ESS} > 0$ and $BM_{n^{in},t}$
    24: if $\lambda_{n,t}^{grid,imp} \leq \overline{\lambda_{n}^{grid,imp}}$ and $BS_{n^{in},t}$ then Charge ESS from grid; $P_{n,t}^{BT} = -P_{n,t}^{BT,chg}$
    25: else Standby ESS and consumption from grid; $P_{n,t}^{BT} = 0$
    26: end if (line 24)
    27: else Normal operation (based on [34])
  28: else $P_{n,t}^{balance} = 0$
    29: if $Tmax_{n^{in},t}$ and $BM_{n^{in},t}$
    30: if $E_{n,t}^{chargeable,ESS} > 0$ then Charge ESS from grid; $P_{n,t}^{BT} = -P_{n,t}^{BT,chg}$
    31: else Standby ESS; $P_{n,t}^{BT} = 0$
    32: end if (line 30)
    33: elseif $Tmax_{n^{out},t}$ and $BM_{n^{out},t}$ and $E_{n,t}^{available,ESS} > E_{n,t}^{desired}$ then Discharge ESS until $E_{n,t}^{desired}$; $P_{n,t}^{BT} = \min\left(P_{n,t}^{BT,dch}, \left(E_{n,t}^{desired} - E_{n,t}^{available,ESS}\right)/\Delta t\right)$
    34: elseif $Tmax_{n^{in},t+1}$ and $BM_{n^{in},t+1}$ and if $E_{n,t}^{chargeable,ESS} > 0$ then Standby ESS; $P_{n,t}^{BT} = 0$
    35: else Normal operation (based on [34])
    36: end if (line 29)
  37: end if (line 8)
  38: Compute power limits $-P_{n}^{contracted} \leq P_{n,t}^{grid} \leq P_{n}^{contracted}$
39: end for
```

The decentralized rule-based low-level strategy follows the logic of the high-level strategy (4-39 of the pseudo-code Table A1), and operates using real-time generation, consumption and ESS powers. An additional condition was incorporated (lines 10, 18, 24, and 30) to regulate ESS charging from the grid. This condition ensures that grid charging is only permitted when: a) the electricity price at t is less than or equal the daily average price ($\lambda_{n,t}^{grid,imp} \leq \overline{\lambda_{n}^{grid,imp}}$) and b) the generation variance is lower than the defined parameter y ($Var_{n,t}^{Pgen} > -y$). These constraints are designed to prevent unnecessary grid consumption costs due to ESS charging during periods of high prices and low expected surplus availability for sharing.

Furthermore, ESS discharge to the grid is controlled by integrating the condition $Cbt_{n,t} > 0$ and limiting the discharge power of the ESS. $Cbt_{n,t}$ is used to limit the discharge power (lines 14 and 33 of the pseudo-code) as formalized in (61). This mechanism ensures that the energy discharged from the ESS does not exceed the expected consumption of other members, thereby avoiding non-optimal operations and improving overall system efficiency.

$$P_{n,t}^{BT} = \min\left(Cbt_{n,t} \cdot P_{n,t}^{BT,dch}, \left(E_{n,t}^{desired} - E_{n,t}^{available,ESS}\right)/\Delta t\right) \tag{61}$$

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Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- Centralized strategies maximize collective economic savings through optimization.
- Decentralized strategies achieve near-optimal performance with minimal computation.
- Decentralized strategies ensure user privacy by operating without data exchange.
- Calculating allocation coefficients closer to operation increase cost savings.
- Decentralized systems facilitate the transition to collective self-consumption.

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Cover letter for Elsevier Applied Energy

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26th December 2025

IKERLAN Technology Research Centre
Paseo Jose Maria Arizmendiarrieta Ibilbidea, 2,
20500 Arrasate – Mondragón. Gipuzkoa (SPAIN)

Dear Editorial Board,

With the present manuscript entitled "**Techno-economic Assessment of Centralized and Decentralized Energy Management Strategies for Energy Sharing in Collective Self-consumption Schemes**" we conduct a techno-economic analysis of two different energy management strategies for collective self-consumption schemes. Energy sharing mechanisms within self-consumption frameworks strongly depend on the regulatory context of each country. Consequently, we identify a need to develop energy management strategies for individual self-consumers who are willing to engage in collective self-consumption, particularly in countries with evolving regulatory frameworks. Both centralized and decentralized energy management strategies offer distinct advantages, such as the global system-wide optimization perspective provided by centralized approaches and the enhanced privacy preservation and computational scalability of decentralized ones. Furthermore, this study addresses the need for an analysis of different allocation coefficient calculation methods, providing evidence-based insights that may support regulators in designing more efficient energy sharing mechanisms.

The main contributions and highlights of the present manuscript are listed here:

- Evaluation of the implications of collective self-consumption adoption for individual self-consumption installations under the Spanish regulatory framework, with only pre-delivery (fixed) allocation coefficients, compared to using post-delivery allocation coefficients as in the Portuguese context.
- An ex-ante (fixed) allocation coefficient calculation is proposed for the Spanish regulation scenario, combining a mixed-integer linear programming optimization algorithm with a data clustering method.
- Development and comparison of a centralized and a decentralized energy management strategy for collective self-consumption within an ex-ante (fixed) allocation coefficient computation.
- Evaluation of both strategies with several regulatory adoptions from the Portuguese context, integrating proportional allocation coefficients (post delivery calculation) and peer-to-peer energy sharing among members.
- Techno-economic assessment and comparison of the centralized and decentralized EMSs approaches.

We believe that our contribution would be of high interest to other researchers focused on energy management strategies for energy sharing in collective self-consumption schemes.

The authors' information is described below:

Ane Feijoo-Arostegui	Ph. D. Student / Researcher at Ikerlan.	afeijoo@ikerlan.es
Luís Rodrigues	Researcher at INESC TEC.	luis.m.rodrigues@inesctec.pt
Dr. Haizea Gaztañaga	Head of Energy Storage and Management team at Ikerlan.	hgaztanaga@ikerlan.es
Dr. José Villar	Head of Energy Markets area at INESC TEC.	jose.villar@inesctec.pt
Dr. Tiago Soares	Senior Researcher at INESC TEC / Lecturer at FEUP.	tiago.a.soares@inesctec.pt
Dr. Ander Goikoetxea	Lecturer at Mondragon Unibertsitatea.	agoikoetxeaa@mondragon.edu

Submission history: These results have not been previously published at any other journal.

Thank you for considering our work.

Yours sincerely,

Mrs Ane Feijoo-Arostegui
IKERLAN Technology Research Centre
Energy Storage and Management Department

What is the novelty of this work?

The novelty of this paper lies in the techno-economic assessment and comparison of centralized and decentralized energy management strategies for energy sharing in collective self-consumption schemes, under evolving regulatory frameworks.

Why do you think the paper is important?

This paper is important as it evaluates energy management strategies for collective self-consumption under regulatory assumptions that reflect current policy trends. By focusing on evolving regulatory frameworks countries, the study highlights the need for flexible EMS designs capable of delivering near-optimal outcomes despite regulatory uncertainty, providing relevant insights for both self-consumers and regulators.

Why the journal should publish it?

We believe that our contribution would be of high interest to other researchers focused on energy management strategies for energy sharing in collective self-consumption schemes.

In submitting this paper I confirm, as corresponding author, that the final submitted manuscript has been shared with all authors listed on the manuscript and that all authors have confirmed their agreement to the manuscript.

Yes, all the authors have confirmed their agreement and the manuscript has been shared.

Has the article been checked by a native speaker with expertise in the field?

Several researchers with expertise in the field have checked the article.