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Fairness in energy communities: Centralized and decentralized frameworks

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ABSTRACT

This research discusses fairness in energy communities while investigating two types of organizations for operation and cost-sharing. On the one hand, centralized architectures consist of operating community assets in a coordinated manner with a central controller before a community manager shares the overall benefits between the users. Four sharing strategies are investigated and implemented in a monthly post-delivery phase. In contrast, in decentralized architectures, each user operates its assets independently. In such frameworks, the costs/benefits are usually shared among users through market-based mechanisms that rely on users' bids. This work then explores the Pool market and Peer-to-peer transactions to investigate the impact of different bidding from the users' perspective. Ultimately, all the proposed centralized and decentralized approaches (10 in total) are assessed based on economic performances at both users' and community levels. Specific attention is paid to fairness within the community, which is challenging. Three indexes derived from economy and game theory are then considered, along with metrics tailored for energy communities. Results from a seven-user community indicate that the pool market systematically returns considerable savings among decentralized frameworks compared to peer-to-peer markets. More importantly, centralized frameworks systematically yield the most significant bill reduction (16 %) and fairer cost allocation compared to decentralized frameworks.

Nomenclature

Abreviations		η	Battery efficiency
		$\overline{P}^b, \overline{E}^b_n$	Battery rated power and capacity of user n
		$p^{b-}_{n,t}, p^{b+}_{n,t}$	Battery charge/discharge of user n at time t
BS1	Bidding strategy 1 - Random bids	$\overline{P}^c$	Maximum import/export power of the EC
BS2	Bidding strategy 2 - Constant bids	P^{c-}_t, P^{c+}_t	Grid import/export of the EC at time t
BS3	Bidding strategy 3 - Proportional bids	$\overline{P}^g_n$	Maximum import/export power of user n
EC(s)	Energy community (ies)	$P^{g-}_{n,t}, P^{g+}_{n,t}$	Grid import/export of user n at time t
EANSV	Equal Allocation of Non-Separable Values	$P^l_{n,t}, P^{pv}_{n,t}$	Load and solar generation of user n at time t
KoR	Keys of Repartition	$P^b_{n,t}, P^s_{n,t}$	Buying/selling power quantity of user n at time t
OPT	Optimization problem	$P^{tb}_{n,t}, P^{ts}_{n,t}$	Power traded to buy/sell of user n at time t
P2P	Peer to peer	π^-, π^+	Grid purchase price and feed-in tariff

(*continued on next column*)

(*continued*)

PR	Proportional allocation	$\pi^{bb}_{n,t}, \pi^{bs}_{n,t}$	Bidding price to buy/sell of user n at time t
PV	Photovoltaic	$\pi^{p2p}_{n,t}$	P2P price for user n at time t
QoS	Quality of service	π^{pool}_t	Pool price for all users at time t
QoE	Quality of experience	$SOC_{n,t}$	Storage state of charge of user n at time t
Symbols		SOC^{ini}_n	Initial state of charge of the user n
B^{ini}_n	Individual bills after the operational stage	$SOC_{\min}$ $SOC_{\max}$	Storage state of charge limits for all users
B_n	Bill of the user n	$u^b_{n,t}$	Storage of user n charging mode at time t {0,1}
β	Minimum savings for all users	u^c_t	Grid power of the EC to export at time t {1,0}
CC^*	Total community costs	$u^g_{n,t}$	Grid power of user n to export at time t {1,0}

1. Introduction

Energy communities (ECs) emerge as a collaborative engagement of consumers in pursuing enhanced energy empowerment as well as

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increased integration of local renewable resources [1]. By the end of 2023, in Europe, there were approximately 10,000 initiatives promoting energy communities and empowering citizens, with diverse national regulations – e.g. 350 implementations in France within a framework of collective self-consumption [2]. Regulation promotes EC initiatives to develop further and explore different mechanisms to encourage collective energy consumption [3].

Despite many definitions found in the literature, ECs consistently comprise the aggregation of several end-users along with different assets (distributed energy resources), either shared or individual, which impacts their operation [4,5]. ECs have been attracting an increasing interest in the research community. Most investigations focus on their organization from both the operational and financial perspectives. Two main types of organizations emerge, with centralized frameworks on one side, and decentralized frameworks on the other.

In the case of centralized frameworks, it is assumed that the EC operates as one single entity, conducting transactions and managing resources collectively. In common applications, a community manager is in charge of the energy management (i.e., the operation) of the community assets and the energy/cost allocation between the community members. Typical operational objectives target the minimization/maximization of financial, technical, and/or environmental criteria [6]. Beyond the operational concerns, one core challenge in the scope of ECs in centralized organizations lies in determining how to distribute energy costs, and/or revenues among individuals once the operational phase is performed. Usually, the bill is determined based on retailer prices. However, when considering a single entity with multiple members, calculating individual bills becomes complex due to the diversity of asset ownership and energy consumption patterns of the members of the EC. Among the approaches for bill repartition (i.e., benefit sharing/cost allocation), various methods, including game theory-based [7], optimization methods [8], and rule-based control techniques [9], are designed for diverse purposes. The primary focus often concerns financial metrics, assessing the impact of different energy management strategies on user's bills after the cost allocation is performed [10]. It is worth to notice that in centralized approaches the community manager may opt for transacting in the energy market, given the contractual agreement with the users [11].

In decentralized frameworks, users manage their assets individually without any coordination at the community level. Rather than billing at retail prices, members of the EC can trade freely with peers, leveraging their energy management. Local energy markets facilitate transactions among community members by establishing common rules. Several studies in the literature have explored market-based transactions [12], including pool markets [13] and peer-to-peer (P2P) trading [14]. In the research on ECs, framing P2P markets as a centrally supervised or entirely decentralized approach remains ambiguous. Numerous papers describe P2P primarily as interactions among peers [15], often overlooking the participants' trading freedom and in most papers, a centralized entity oversees the transactions, somewhat similar to pool markets [16].

Regardless of the market mechanisms, the results of a decentralized organization are strongly impacted by the users' bidding strategies. Indeed, peers must determine both the bidding quantity (e.g., given by the operational part) and the corresponding bidding price for the energy during the market sampling period. Defining the bidding prices is crucial in the bidding process to determine the market outcomes [17]. Moreover, accurately representing how users set their bids poses a notable challenge and has not been widely investigated in the literature. A study on day-ahead bidding strategies is proposed in Ref. [18], in which a stochastic model is used to evaluate risk scenarios and design the users' bidding prices while considering the knowledge of real-time and day-ahead prices. Similarly, the research in Ref. [19] proposes a community reference price and compare two trading algorithms (Multi-unit-double-auction (MUDA) and P2P). A reference price is based on the knowledge of the spot market and the renewable energy availability, and from it, random decision prices are designed following a deviation with a normal distribution around the reference price. Beyond the market mechanisms, a discussion could focus on the impact of assumptions, such as user bidding strategies and clearing mechanisms on the market [20]. Additionally, choosing a trading partner (i.e., pairing methods) may significantly influence the market outcome and impact the benefit sharing among the users. Consequently, this hinders the individual's willingness to engage in peer-to-peer trading.

Furthermore, it is worth noting that social acceptance and fairness are important features which should be considered when assessing the performances of energy communities. Users willing to join an EC may be more interested in a wide range of metrics beyond financial concerns, such as the fairness of the organization of the EC, or the fact that energy is supplied from local sources. It is fundamental to identify the appropriate method for fair cost/benefit allocation, assuming fairness indexes can be defined and accepted by the members of the EC [21]. In this context, how to determine the method to use? Factors to consider include explainability, asset ownership, consumption patterns, and individual engagement within the EC, among other criteria [22]. Some studies have then attempted to introduce fairness indexes in their approaches as performance indexes in addition to cost reduction and/or self-consumption ratios.

Fairness is a transversal concept encompassing several fields of knowledge. For instance, it has been a significant concern in power systems to avoid congestion in the communications networks. In that context, some metrics have gained popularity because of their simplicity, such as the Jain index [23], which focuses on equally sharing resources. However, in the context of ECs, the Jain index does not represent the marginal individual's contribution to the community. Fairness in ECs can be considered in both centralized and decentralized frameworks. For instance, a P2P energy-sharing method was proposed in Ref. [24] to account for users' willingness to pay to a preferred user while incorporating fairness. However, the proposition was not explicitly demonstrated. Other key performance indicators used to assess P2P trades include MinMax, quality of service (QoS) [15], and quality of experience (QoE) [25]. The MinMax index measures fairness by analyzing the differences between the higher and lower resource allocation values, such as trading prices or allocated costs. The QoS index ensures the equal distribution of traded volume for each peer, similar to the Jain index. Likewise, QoE considers the deviation from the mean value. Like the mentioned indexes, it aims to achieve an allocation that ensures an equal share of resources [26].

It is then important to define fairness within the specific context of ECs. Consideration should be given to the marginal contributions of each member to the overall benefits compared to a baseline scenario – e.g. in case users are not organized as an EC. In this context, Shapley's value becomes relevant [27], as it is regarded as a "just" approach by factoring in individual contributions to the "grand coalition", i.e. the EC [28]. As such, in Ref. [4], a benefit sharing method is proposed to account for marginal cost redistribution, while also considering network constraints. In this way [4], ensures the proposed cost allocation fairness. Similarly, in Ref. [29], a fair ex-post cost allocation method is presented based on "nucleolus", a concept addressing fairness by minimizing the dissatisfaction of EC members.

Other methods account for individuals' contributions, such as in Ref. [30], in which a fairness index is inspired by the Vickrey-Clarke-Groves (VCG) mechanism from auction theory. The VCG is a mechanism where bidders submit sealed bids, which incentivizes truthful bidding, as bidders have no incentive to bid anything other than their true valuation for the item. The proposed approach in Ref. [30] involves determining each user's contribution by optimizing the system after removing one member from the energy community, similar to Shapley's value calculation. The result is a "contribution distribution" per user, a technique designed to ensure "fairness" by considering the worst-case scenario for the EC. Nevertheless, this method has the same limitations as the Shapley value, primarily concerning the necessity to

compute all combinations of the same problem for every coalition.

Furthermore, some methods introduce rule-based allocation methods and measure their effectiveness using different metrics in collective frameworks [31]. This includes assessing individual rationality, which involves reducing costs through centralized resource management and projecting them for the coming years. While these assumptions may be reasonable, they do not adequately account for fairness in the allocation process.

Similarly, in Ref. [22], several allocation methods regarding fairness, stability, and computation are compared. However, the comparison is primarily qualitative; fairness must be better defined. Furthermore, in Ref. [32], axioms for fairness are described, and various methods are briefly explained, including the allocation approaches mentioned. Nevertheless, assessing fairness is more complex. In energy communities, fairness encompasses distributional issues like affordability, non-discrimination, and transparency [33]. In economic theory [34] a fair allocation, according to Ref. [34] is one where agents are satisfied with their share of benefits and do not envy others, constituting a "just" allocation. This concept can be a proxy for public adoption of the developed socio-technical solution. Table 1 classifies the literature review in the context of ECs, especially for fairness assessment.

The research presented in this work compares quantitatively fairness indexes found in literature and apply them to the context of ECs, ultimately comparing two paradigms for EC management: centralized and decentralized (market-based) frameworks. To the author's knowledge, this is the first work to compare different fairness indexes quantitatively applied to various approaches. Furthermore, the frameworks are implemented through a two-stage methodology similar to the approach in Ref. [10]. Daily energy management relies on a deterministic profile, and cost allocation (including revenue distribution) is conducted monthly, considering users' net load profiles after energy management (in a post-delivery approach). Moreover, the decentralized framework's bidding strategies and market mechanisms are discussed simultaneously.

Overall, four cost allocation strategies are investigated (for centralized frameworks), and three bidding strategies for both, Pool and P2P markets (for decentralized organizations). This work underscores the importance of selecting appropriate fairness measures based on the specific characteristics of the energy community, users' profiles, and selected framework. Fig. 1 shows the organization of this document, covering the investigated methods, notably separating management from allocation stages for both centralized and decentralized frameworks. Finally, all methods are compared based on performance metrics such as bill savings and fairness.

The main contributions of this work are.

- A quantitative comparison of four fairness indexes applied to ten different methods for cost allocation encompassing centralized and decentralized frameworks.
- Assessing two market mechanisms (Pool and P2P) and three bidding strategies for decentralized frameworks.
- An optimization method that allocates collective benefits while designing internal purchasing and selling prices within the EC, ensuring more significant bill savings for individuals.
- The qualitative and quantitative discussions and comparison of the two frameworks across technical, economic, and fairness criteria, emphasizing the importance of perspective by examining these factors from both the community's and end-users' viewpoints.

This document is organized as follows. Section 2 outlines the case study and the generic equations to model the energy community and introduces the fairness metrics considered in this research. Section 3 describes the decentralized framework, explaining the bidding strategies and the market clearing mechanisms implemented in the frameworks. Section 4 presents a centralized framework in which an optimization-based approach and other cost allocation methods are explored. Results and discussion are given in Section 5. Finally, conclusions are provided in Section 6.

2. Methodology

2.1. System model

Consider a residential community of N members, as depicted in Fig. 2, where each member can install photovoltaic panels and/or a storage system, primarily intending to minimize their energy costs. As illustrated in the zoomed-in part of Fig. 2, each user has a load profile $P^{l}_{n,t}$ and a photovoltaic production $P^{pv}_{n,t}$ as parameters. In contrast, the energy storage system charging and discharging powers ($P^{b-}_{n,t}$, $P^{b+}_{n,t}$) are controllable variables.

The energy management could be performed individually or cen-

Table 1
Scope of work and contribution of the article in the context of fairness in energy communities.

Ref	Control type	Settlement	Energy allocation	Fairness metric
[6]	Centralized	KoR	Day ahead and real time	–
[9]	Centralized	KoR		–
[11]	Centralized	KoR	Postdelivery	–
[14]	Centralized	P2P market		–
[7]	Centralized	KoR	Day ahead	≈
[35]	Centralized	Game theory and KoR	Day ahead	Δ index
[16]	Decentralized	P2P market		–
[21]	Decentralized	P2P market		Jain index
[25]	Decentralized	Multilayer market based		Jain index/QoE
[15]	Centralized & decentralized	P2P market		QoS,minmax
[19]	Centralized & decentralized	MUDA and P2P		–
[20]	Centralized & decentralized	P2P and order book Market		–
[13]	Centralized & decentralized	Pool market and KoR	Postdelivery	≈
[36,37]	Centralized & decentralized	KoR	Day ahead/Postdelivery	–
[4]	Centralized & decentralized	Game theory based KoR	Real time	Bill decrease
[8]	Centralized & decentralized	Individual bill at the meter - OPT		–
[10]	Centralized & decentralized	KoR and Game theory	Postdelivery	–
[38]	Centralized & decentralized	Game theory based OPT	–	≈
[29]			Postdelivery	
[39]	Centralized & decentralized	Game theory reward allocation		≈
This Work	**Centralized & decentralized**	**KoR/OPT & P2P/Pool market**	**Postdelivery**	**Jain/minmax/QoE/ Δ**

KoR: Keys of Repartition/Ruled based allocation, MUDA: Multi-unit-Double-Auction, Δ index: Distance index.

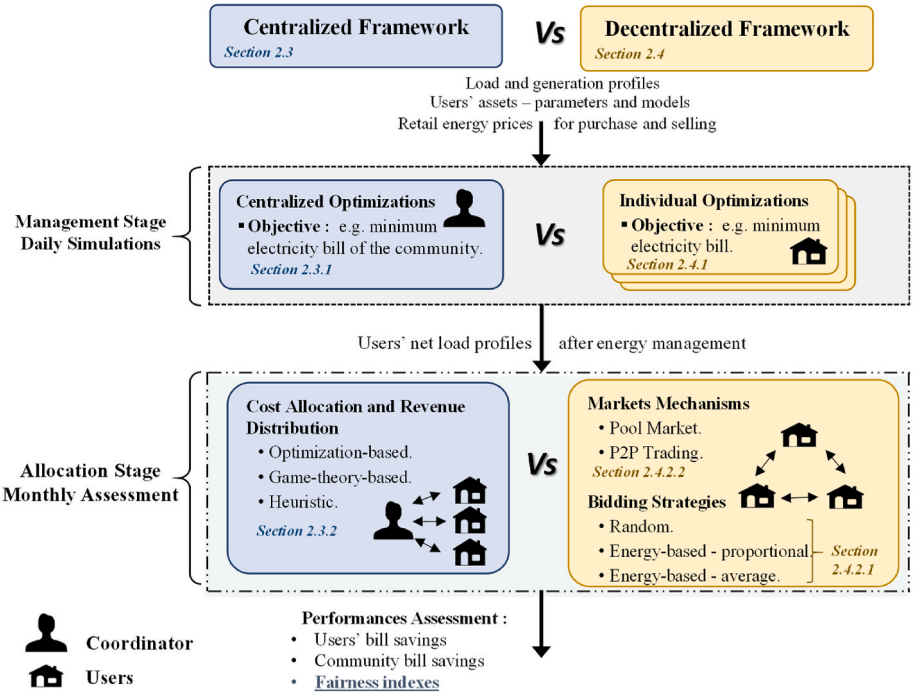

Fig. 1. Categorizing the main two-stage approaches implemented in this research.

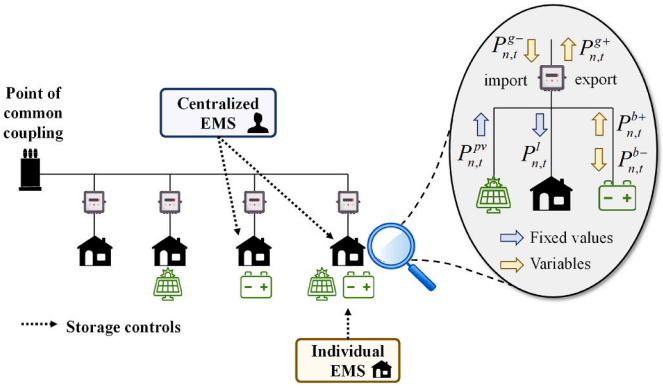

Fig. 2. Operational stage: centralized vs individual energy management.

trally (with the help of a coordinator, as illustrated in Fig. 2). The individual operation focuses on optimizing resources primarily for individual benefit, aiming to reduce the purchased power $P^{g-}_{n,t}$ and increase the export of power to the grid $P^{g+}_{n,t}$. Alternatively, users can join an EC where an overarching entity manages the community, aiming for collective benefits. Such a collective approach ultimately results in advantages for individual users as well.

The equations describing the individuals are represented as constraints in an optimization model, as detailed in Section 2.4.1. These constraints are generic and can be applied to various objectives within the same optimization problem.

2.1.1. Individuals: end-users' model

Equation (1) describes the power balance for an individual, which is depicted in the zoom-in part of Fig. 2. To avoid simultaneous consumption/production at the meter level a binary variable $u^{g}_{n,t}$ (representing if the grid export is active or not) is introduced in eq. (2), and additionally, to prevent exceeding the maximum provision/injection of power from the grid $\overline{P}^{g}$. Likewise, eq. (3) ensures similar properties for the energy storage system with the use of the binary variable $u^{b}_{n,t}$ and a maximum capacity $\overline{P}^{b}$ to avoid any simultaneous charging/discharging.

$$P^{l}_{n,t} = P^{pv}_{n,t} + P^{b+}_{n,t} - P^{b-}_{n,t} + P^{g-}_{n,t} - P^{g+}_{n,t} \quad \forall (n,t) \in \{N,T\} \tag{1}$$

$$\begin{cases} 0 \le \mathrm{P}^{g+}_{n,t} \le \mathrm{u}^{g}_{n,t} \times \overline{\mathrm{P}}^{g} \\ 0 \le \mathrm{P}^{g-}_{n,t} \le \left(1 - \mathrm{u}^{g}_{n,t}\right) \times \overline{\mathrm{P}}^{g} \end{cases} \quad \forall (\mathrm{n},\mathrm{t}) \in \{\mathrm{N},\mathrm{T}\} \tag{2}$$

$$\begin{cases} 0 \le \mathrm{P}^{b+}_{n,t} \le \mathrm{u}^{b}_{n,t} \times \overline{\mathrm{P}}^{b} \\ 0 \le \mathrm{P}^{b-}_{n,t} \le \left(1 - \mathrm{u}^{b}_{n,t}\right) \times \overline{\mathrm{P}}^{b} \end{cases} \quad \forall (\mathrm{n},\mathrm{t}) \in \{\mathrm{N},\mathrm{T}\} \tag{3}$$

As for the energy storage system, residential lithium-ion batteries are considered with conventional linear constraints. Equation (4) describes the typical update of the state of charge (SOC) considering the charge and discharge of the battery while accounting for its total energy capacity $\overline{E}^{b}_{n}$ and efficiency η. Equation (5) guarantees the SOC of the battery to be within a range of $[0-1]$. Finally, eq. (6) represents the energy conservation in the energy storage system.

$$SOC_{n,t+1} = SOC_{n,t} + \left(\eta \times P^{b-}_{n,t} - \frac{P^{b+}_{n,t}}{\eta}\right) \times \frac{dt}{\overline{E}^{b}_{n}} \quad \forall \quad (n,t) \in \{N,T\} \tag{4}$$

$$SOC_{\min} \le SOC_{n,t} \le SOC_{\max} \quad \forall \quad (n,t) \in \{N,T\} \tag{5}$$

$$\begin{cases} SOC_{n,t=0} = SOC^{ini}_{n} \\ SOC_{n,t=T} = SOC_{n,t=0} \end{cases} \quad \forall\, n \in N \tag{6}$$

2.1.2. Community's model

Equation (7) is introduced to supplement eq. (1) and consider the energy community a unified entity. Which captures the power flow, covering the supply P^{c-}_{t} from and P^{c+}_{t} the injection to the grid from the EC. Similarly to eq. (2), eq. (8) prevents the EC from producing/consuming more than its maximum capacity $\overline{P}^{c}$. Additionally, the flows are guaranteed to avoid simultaneous energy import/export from/to the upstream grid using the binary variable u^{c}_{t}.

$$P_t^{c+} - P_t^{c-} = \sum_{n \in N} \left(P_{n,t}^{g-} - P_{n,t}^{g+} \right) \forall\, t \in T \tag{7}$$

$$\begin{cases} 0 \le \mathrm{P}_\mathrm{t}^{\mathrm{c}+} \le \mathrm{u}_\mathrm{t}^{\mathrm{c}} \times \overline{\mathrm{P}}^{\mathrm{c}} \\ 0 \le \mathrm{P}_\mathrm{t}^{\mathrm{c}-} \le \left(1 - \mathrm{u}_\mathrm{t}^{\mathrm{c}}\right) \times \overline{\mathrm{P}}^{\mathrm{c}} \end{cases} \quad \forall \mathrm{t} \in \mathrm{T} \tag{8}$$

2.2. Fairness in ECs: equity metrics

This research underscores the significance of fairness within ECs while assessing the performance of different operating modes. Evaluating the fairness of a particular cost allocation method is challenging, given the inherent complexity of achieving equity in the organization of an EC. This work discusses the concepts of equity and fairness in resource allocation for users in an energy community. In this study, equity refers to the equal allocation of costs/benefits for all users, regardless of their contribution or asset composition. Conversely, fairness considers users' diverse profiles and assets to ensure justice for all participants relatively to their contribution to the community.

As previously discussed, various methods measure "fairness" in different contexts, such as QoS, QoE, and MinMax [15], which are often used in conjunction with the Jain index. Moreover, the definition of equity provided by the Jain index is occasionally reevaluated [26]. However, these methods are based on the equal allocation of resources, meaning they determine how far the individual allocation of resources is from the mean of the energy community, which focuses on assessing equality and not necessarily fairness.

This research compares four fairness indexes to avoid undue complexity, keeping in mind the need to explain findings to end-users in EC who may not be familiar with technical developments, which highlights the importance of selecting appropriate metrics.

The first considered method relies on the Jain index [40], a widely recognized approach applied to communication networks to prevent congestion. This method is designed to achieve equal distribution of resources, hence, to ensure *equity*. Equation (9) outlines the index computation, with the variable x_n representing a value function. Essentially, it is the square of the ratio between two power means of the x_n: the arithmetic mean and the quadratic mean. According to the power means inequality, this ratio lies within the interval [0, 1]. Furthermore, the value is equal to 1 only when all x_n are identical. Hence, the closer the Jain index is to 100 %, the higher the equity allocation. In the context of ECs x_n may correspond to the individual bill savings.

Similar to the Jain index, the MinMax and QoE indexes are applied and adapted to the context of ECs. Their calculation is given in eqs. (10) and (11), respectively. As discussed, the MinMax index measures fairness by comparing the highest and lowest bill savings of the participants within the EC. The QoS is equivalent to the Jain index, as described in Ref. [25] and included within eq. (9). Additionally, the QoE considers the comparison of the standard deviation σ and the maximum standard deviation, described in Ref. [26] as the difference between the maximum and minimum cost allocation, and is detailed in eq. (11). It is worth mentioning that eqs (9)–(11) indexes are designed to evaluate the deviation from the mean value of the distribution by comparing the standard deviation (QoE) or the minimum and maximum values (MinMax). These indexes were developed for other contexts in energy systems to ensure an equal share of resources, which may differ from fairness.

In contrast, the distance index (Δ) [35,41] is a tool that quantifies the difference between a billing vector generated by a specific billing mechanism B_n and the billing vector associated with a benchmark of fairness, typically the Shapley value billing mechanism (B_n^*). Equation (12) provides the calculation for the Δ index. Note that the Δ index is primarily used to measure the extent of variation between two mechanisms. This study has modified it to simplify the comparison with the other indexes presented in this work. Hence, when the compared method closely resembles the benchmark, Δ is closer to 100 %. However, it is important to mention that as Δ is comparing to another billing mechanism, it requires calculating such cost allocation first.

$$J = \frac{\left[\sum_{n=1}^{N} x_n\right]^2}{n \cdot \sum_{n=1}^{N} x_n^2} \tag{9}$$

$$MinMax = \frac{\min(x_n)}{\max(x_n)} \tag{10}$$

$$QoE = 1 - \frac{\sigma}{\sigma_{\max}} = 1 - \frac{\sigma}{(\max B_n - \min B_n)} \tag{11}$$

$$\Delta = 1 - \sum_{n=1}^{N} \left| \frac{B_n}{\sum_{m=1}^{N} B_m} - \frac{B_n^*}{\sum_{m=1}^{N} B_m^*} \right| \tag{12}$$

2.3. Centralized framework: operation and cost allocation

2.3.1. Operation: community level

The EC could act as if it was one entity procuring merely the required energy from the grid and selling the surplus after allocating the shared energy among its members. A centralized operation enables its coordinator to control the setpoints of its available flexible assets.

Therefore, the costs are not directly related to individual users' import/export but to a collective aggregation of consumption and production. Thus, the aim is to minimize the total costs of the EC, as described in eq. (13) for the overall optimization problem. Here, the retailer charges π^- for electricity consumption and pays π^+ for the surplus.

$$\begin{aligned} \min\, CC = & \sum_t \left(\pi^- \times P_t^{c-} - \pi^+ \times P_t^{c+} \right) \cdot dt \\ & s.t. \quad (1)\&(3) - (8) \end{aligned} \tag{13}$$

2.3.2. Settlement: costs allocation

After the operational part, the costs must be redistributed among the community members. In this subsection, four types of cost allocation will be described and further compared in Section 3.3.1 with the decentralized framework.

- **Shapley Value**

The Shapley value is an approach widely known for ensuring individual rationality, efficiency, stability, and meeting various fairness criteria in game theory. It is based on each participant's marginal contribution to the overall system's performance.

In this research, the EC is defined by the set of its participants N, also called a "grand coalition." Let S be a subset of participants, also defined as a coalition.

The Shapley value assesses an individual's contribution to the grand coalition (i.e., the EC) by iteratively removing each participant from the coalition. It then evaluates the collective energy management of the new EC (excluding the removed participant), and the value of the coalition $v(S)$ corresponds to the total energy bill of the EC in the subset S. It then compares it with the value of the grand coalition $v(S\backslash\{n\})$. Hence, the marginal contribution of each individual is computed as the difference in the total costs between the grand coalition and the coalition formed by the subset $v(S) - v(S\backslash\{n\})$. The Shapley value is expressed in eq. (14) [28]. Through the computation of the Shapley value (Sh_n) for user n, a suitable distribution is determined, accounting for each user's contribution to the grand coalition.

$$Sh_n(N,v) = \sum_{S \subseteq N \setminus \{n\}} \frac{(|S|-1)!(|N|-|S|)!}{|N|!} [v(S) - v(S \setminus \{n\})] \quad (14)$$

Since the value of the coalition $v(S)$ corresponds to the centralized operational costs of each subset S, the Shapley value yields the cost allocation for each member of the EC. However, calculating each coalition's value requires computing the centralized optimization in eq. (13) for every subset S, which demands significant computational effort due to its combinatorial nature. Furthermore, as a rule-based approach, it may not encompass other aspects, such as the specific preferences of individual users. Given the complexity of the Shapley value calculation, some research works have depth in its approximation to reduce computational time and achieve similar results to the Shapley value. The proposed method in Ref. [27] relies on creating a virtual user whose power profile is the average of the other users in the community to calculate the community's marginal contributions. The main assumption is based on the concept that the Shapley value can also be seen as the mean of the expected marginal contribution of every possible coalition. For a detailed explanation of the Shapley value as part of the cost allocation methods for ECs, the reader may refer to Ref. [10] and to Ref. [27] for a method for approximation. In this work, we focus on the exact calculation of the Shapley value to assess the Δ index and avoid methods that approach to the mean value of the distribution, such as the other fairness indexes.

- **Equal Allocation of Non-Separable Values (EANSV)**

The EANSV method involves comparing the inherent gap between the individual initial bill over a month B_n^{ini} (i.e., the result of the individual operation, further developed in eq. (18)) and the collective bill CC^* (i.e., the optimal costs of the centralized energy management). Moreover, it determines each individual's "non-separable values," which is similar to the individual contributions to the energy community with the Shapley value.

Moreover, to understand the meaning of "non-separable costs," it is first necessary to define "separable costs" as the individual charges before joining the energy community i.e., B_n^{ini}. Hence, the "non-separable costs" embody the difference between the collective bill and the sum of the "separable costs," which is reflected in the numerator of eq. (15) [33]. Among many methods to allocate the "non-separable costs," the EANSV first assigns "separable costs" to each end-user and then splits the "non-separable costs" among the members equally. In summary, this method shares the benefits by accounting for the individual bill and dividing the collective savings —calculated by subtracting the total of individual bills from the collective bill —equally among all members, as in eq. (15).

$$B_n = B_n^{ini} + \frac{\left(CC^* - \sum_{n \in N} B_n^{ini}\right)}{N} \quad (15)$$

- **Proportional Allocation (PR)**

The difference between individual and collective bills yields community savings, which can be distributed among the users in the form of bill decreases. In the PR method, the bill decrease is proportionally assigned based on each user's initial optimal bill relative to the sum of all the bills. This approach is based on the Nash equilibrium concept.

Equation (16) describes the proportional bill allocation. The added absolute value allows considering users with negative net bills (i.e., prosumers). In case all the members of the EC are net consumers, i.e., their PV generation does not surpass their energy consumption, this allocation is equivalent to the typical proportional-based bill [36].

As this repartition leads to equal savings for all participants, the allocation may be unfair since each user has a different power profile and diversity of assets. Therefore, the savings should be allocated accordingly.

$$B_n = B_n^{ini} - \left[\frac{|B_n^{ini}|}{\sum_{n \in N} |B_n^{ini}|} \times \left(\sum_{n \in N} B_n^{ini} - CC^* \right) \right] \quad (16)$$

- **Optimization-Based Cost Allocation (OPT)**

The last investigated strategy to centrally allocate the costs is grounded in an optimization model, which aims at finding adequate prices for the given consumption/generation of the energy community (i.e. the meter value). It operates on the principle of centralized resource sharing that could be performed by either an aggregator or a community manager. Therefore, each end-user can spend less money simply by being part of the energy community. Exploiting the inherent gap between exchanging individually relying on the grid or in a community, the objective is to maximize the savings of the users in the EC.

The overall optimization problem in the proposed cost allocation is described in eq. (17), in which the inputs from the coordinated operation are the individual power export $P_{n,t}^{g+}$ over a settlement period T (e.g., a month), and the individual power consumption $P_{n,t}^{g-}$ over T. The optimization variables π^+ and π^- correspond to the a posteriori settlement prices, for selling and purchasing respectively. A variable β is defined to comply with the maximization of the minimum savings of all the users, as in Ref. [10]. The constraint $\sum_n B_n - CC^* \leq 0$ ensures that the total costs are efficiently shared, i.e. the total costs of the new repartition should be at most the collective bill using the centralized approach. This optimization method gives the chance to users to get a bill repartition and additionally the possibility to get even lower bill.

$$\begin{aligned} &\max \beta \\ &s.t. \\ &B_n = \left(\pi^- \times \sum_t^T P_{n,t}^{g-} - \pi^+ \times \sum_t^T P_{n,t}^{g+} \right) \times dt \quad \forall n \in N \\ &\sum_n B_n - CC^* \leq 0 \\ &\beta \leq \frac{B_n^{ini} - B_n}{B_n^{ini}} \quad \forall n \in N \end{aligned} \quad (17)$$

2.4. Decentralized framework: individual operations and market-based cost allocations

2.4.1. Operation: individuals' model

In a decentralized framework, users manage their resources individually and either trade with other users within the EC or deal with their retailer. The retailer determines the prices by considering different factors, policies, and regulations [42]. For simplicity, in this work, the prices are considered flat and fixed for the billing period.

Furthermore, individuals are assumed to be primarily motivated by their interests, aiming to minimize their energy imports based on the purchase price while gaining additional revenue through exporting/selling their potential surplus to the grid. Other easy-to-model motivations could be integrated with the presented methodologies – e.g., maximization of self-consumption and/or self-sufficiency.

The individual operation is presented as an optimization problem that minimizes the individual bill as if the users would trade with the retailer only, as described in eq. (18).

$$\sum_{n \in N} \min B_n^{ini} = \sum_{n \in N} \min \sum_{t \in T} P_{n,t}^{g-} \times \pi^- - P_{n,t}^{g+} \times \pi^+ \text{s.t} \quad (1)-(6) \quad (18)$$

2.4.2. Settlement: post-delivery markets

In this research, the local energy market is performed in a post-delivery fashion, considering the individual operation as a first stage, which determines the power profiles over a month. Once the community management is performed, the power values at the meter level are known for all the community users at a half-hourly resolution – i.e. the purchased power $P^{g-}_{n,t}$ and the exported surplus $P^{g+}_{n,t}$. Then, the settlement phase with the allocation of energy/cost between the community participants can occur, for instance, monthly.

In decentralized frameworks, that allocation conventionally takes the form of market-based operations in which every user generates bids before the market mechanism occurs to allocate the quantities between players. Those mechanisms will be explicit in subsection 2.4.2.2 as a support of the discussion on bidding strategies, one of the contributions of this work, often neglected in the literature.

In practice, buyers and sellers generate bids in quantity (in kWh, i.e., quantities are known from the operational stage in this approach) and price (in c€/kWh) for selling or buying energy. At every market time resolution (30 min here), the cost/profit of each user is influenced by the market mechanism and their bids relative to other users' bids. At this stage, it is essential to recall that the settlement phase is then performed in a post-delivery fashion. Users only bid in prices (i.e., quantities correspond to the power meter values) - with a bidding selling price π^{bs} when exporting energy (i.e. $P^{g+}_{n,t} > 0$) and a bidding buying price π^{bb} when importing energy (i.e. $P^{g-}_{n,t} > 0$). Also, the bidding space can be defined with the retail buying price π^{-} as an upper bound and the retail selling price π^{+} as a lower bound. This then ensures a benefit from a baseline case (i.e., the bill charged at retailer's prices) for both buyers/sellers. To discuss the impact of bidding behavior, three strategies are proposed and compared in this study.

2.4.2.1. Bidding strategies (BS).

- *Bidding Strategy 1 – Random Bids (BS1):*

Similar to the proposition in Ref. [43], one classical bidding approach when investigating market mechanisms is to account for random behaviors. The bidding prices for selling/buying are generated randomly with a uniform law within the bounds and depending on the import/export status of the user n at time t.

$$\begin{cases} P^{g-}_{n,t} > 0 \Rightarrow \pi^{bb}_{n,t} = U(\pi^{+}, \pi^{-}) \text{ and } \pi^{bs}_{n,t} = 0 \\ P^{g+}_{n,t} > 0 \Rightarrow \pi^{bs}_{n,t} = U(\pi^{+}, \pi^{-}) \text{ and } \pi^{bb}_{n,t} = 0 \end{cases} \quad \forall\, (n,t) \in \{N, T\} \tag{19}$$

- *Bidding Strategy 2 – Constant Bids (BS2):*

In the second strategy, the bidding prices remain constant throughout the settlement period (i.e., one month). They are set at the average value between the retail selling and purchasing prices, maintaining the same price for both purchasing and selling users. Equation (20) outlines the proposed strategy.

$$\begin{cases} P^{g-}_{n,t} > 0 \Rightarrow \pi^{bb}_{n} = \dfrac{\pi^{-} + \pi^{+}}{2} \text{ and } \pi^{bs}_{n} = 0 \\ P^{g+}_{n,t} > 0 \Rightarrow \pi^{bs}_{n} = \dfrac{\pi^{-} + \pi^{+}}{2} \text{ and } \pi^{bb}_{n} = 0 \end{cases} \quad \forall\, n \in N \tag{20}$$

- *Bidding Strategy 3 – Proportional Bids (BS3):*

Given that the power profiles are derived from the operational stage, the bidding prices are automatically generated proportionally to the meter value, normalized by the recorded maximum over the period T. The last proposed bidding strategy is given in eq. (21).

$$\begin{cases} P^{g-}_{n,t} > 0 \Rightarrow \pi^{bb}_{n,t} = \pi^{+} + (\pi^{-} - \pi^{+}) \times \dfrac{P^{g-}_{n,t}}{\max_T\left(P^{g-}_{n,t}\right)} \text{ and } \pi^{bs}_{n,t} = 0 \\ P^{g+}_{n,t} > 0 \Rightarrow \pi^{bs}_{n,t} = \pi^{+} + (\pi^{-} - \pi^{+}) \times \dfrac{P^{g+}_{n,t}}{\max_T\left(P^{g+}_{n,t}\right)} \text{ and } \pi^{bb}_{n,t} = 0 \end{cases} \quad \forall\, (n,t) \in \{N, T\} \tag{21}$$

After generating the bidding prices, the subsequent phase involves establishing the market clearing mechanism to allocate the quantities at the settled price(s). This depends on the chosen market mechanism, as elaborated further in subsection 2.4.2.2. Following the completion of transactions using either peer-to-peer or pool market mechanisms, the prices and quantities are determined, allowing for the calculation of the bill.

2.4.2.2. Market mechanisms.

At every time step in the post-delivery settlement phase, markets can be cleared once all the users' bids are performed. The objective of that phase is to determine at which price every user will purchase or sell energy to ultimately compute the bills over an entire month.

- Pool market:

The first market mechanism investigated in this work corresponds to a conventional pool market that results in a single market price π^{pool}_{t} (or market clearing/uniform price) at which the energy is purchased and sold for all the users entering the market. In practice, the selling bids are ranked in ascending order relative to the prices, while the buying bids are ranked in descending order. As shown in Fig. 3, the clearing prices ultimately intersect the aggregated demand and supply curve. Same as in conventional power systems, the merit order is stablished by the selling bids starting with the least expensive, up to the most expensive bid, activated in that order to meet demand. The last activated selling bid sets the price. In the given example, the price corresponds to the selling price bided by user n. User n will purchase its entire load (i.e., the transacted buying power $P^{tb}_{n,t}$) at the market price, while user n will sell part of the export (i.e., the transacted selling power $P^{ts}_{n,t}$) at this rate π^{pool}_{t} and any remaining quantity at the retail tariff. Indeed, any quantity of energy purchased or sold outside the market will be transacted at the retail tariffs and will be deemed outside the market. Implicitly, there is

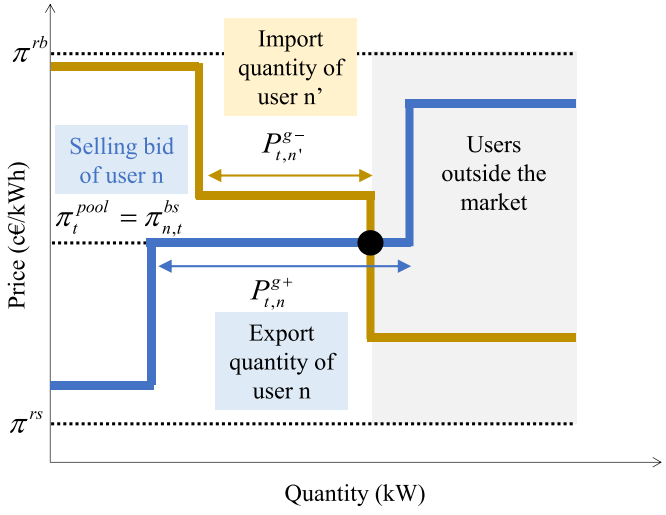

Fig. 3. Description and functioning process of the pool market clearing price.

no market if the minimum of all the selling bid prices is above the maximum of all the buying bid prices. Equation (22) describes the bill for a typical consumer and a producer with this clearing mechanism.

$$\sum_t B_{n,t} = \begin{cases} P^{g-}_{n,t} > 0 \Rightarrow \sum_t \left[\left(P^{g-}_{n,t} - P^{tb}_{n,t} \right) \times \pi^{-} + P^{tb}_{n,t} \times \pi^{pool}_{t} \right] \\ P^{g+}_{n,t} > 0 \Rightarrow \sum_t \left[- \left(P^{g+}_{n,t} - P^{ts}_{n,t} \right) \times \pi^{+} - P^{ts}_{n,t} \times \pi^{pool}_{t} \right] \end{cases} \quad \forall\ n \in N \tag{22}$$

- *Peer to Peer (P2P)*

In contrast to pool markets, in which a central market operator sets the clearing price and oversees the transactions, in the P2P frameworks, users directly interact with each other. The decentralized trading principle among peers is upheld by the freedom to choose trading partners. However, without knowing the user's preference for trading partners, this research implemented a P2P decentralized mechanism based on [44], which proposes a random and anonymous pairwise trade with bargaining.

Algorithm 1 describes the P2P market mechanism considered in this research. In the first step, the users submit their bids without knowledge of other users' quantities or prices by using a given bidding strategy among the ones proposed above. Similar to the pool market, users may be excluded from the market since they bid too low as a buyer or too high as a seller. In the second step, users are paired randomly (i.e., the transaction $tr \in \Gamma$ is a random cobination of users' indexes). This may lead to some users not getting paired even if their bid is appropriate for trading.

It is important to mention that users get diverse prices at each transaction $\pi^{p2p}_{n,t,tr}$, since the traiding partners bid at different prices. Additionally, the users may trade with several other users simultaneously to sell all their production or supply their whole load. Notice that the bill accounts for all possible trades during the same sampling time. Any remaining power not involved in market transactions must be transacted with the retailer. It is worth to remark that if there is short local supply or if the prices do not define a transaction among peers, the users will trade as usual at the retail tariff.

Algorithm 1. :P2P market clearing mechanism

Inputs: $P^{g-}_{n,t}, P^{g+}_{n,t}, \pi^{-}, \pi^{+}, \pi^{bb}_{n,t}, \pi^{bs}_{n,t}$
Output: B_n
For $t \leftarrow 0$ to T do
$\pi^{p2p}_{n,t,tr} = \pi^{bb}_{n,t}$// Users transact at auction pay-as-bid

$$B_{n,t} = \begin{cases} P^{g-}_{n,t} > 0 \Rightarrow \sum_t \left[P^{g-}_{n,t} \times \pi^{-} + \sum_{tr} P^{tb}_{n,t,tr} \times \left(\pi^{p2p}_{n,t,tr} - \pi^{-}_{t} \right) \right] \\ P^{g+}_{n,t} > 0 \Rightarrow \sum_t \left[- P^{g+}_{n,t} \times \pi^{+} - \sum_{tr} P^{ts}_{n,t,tr} \times \left(\pi^{p2p}_{n,t,tr} - \pi^{+}_{t} \right) \right] \end{cases} \quad \forall\ (n,t) \in \{N,T\}$$

//Calculate the bill
end
$B_n = \sum_t B_{n,t}$// Calculate the total bill over T

3. Results and discussion

3.1. Study case

The proposed frameworks are tested over a real EC, including seven households in Le Cailar, south of France [10]. Members 3 and 7 act as consumers (i.e., they do not have PV production); the remaining users are prosumers. Table 2 describes the users' installed capacities. Additionally, the storage system round trip efficiency is set at 95 %.

Load and solar generation profiles are based on local measurements conducted in March 2021, spanning a one-month duration at a 30-min time step. The simulation uses Pyomo in Python for optimization, employing Gurobi as the solver. Moreover, the energy market implementation uses the Python library "pymarket" [45], which is designed to test different market mechanisms. The retailer's considered buying and selling prices are fixed at 25 c€/kWh and 10 c€/kWh, respectively.

Table 2
Household parameters of the considered community.

Member	1	2	3	4	5	6	7
PV [kW]	3.2	6.12	–	3.2	3.2	6.4	–
Battery [kW/ kWh]	5/ 9.8	5/ 9.8	5/ 9.8	5/ 9.8	5/ 9.8	5/ 9.8	5/ 9.8

3.2. Operation results

This section presents and analyzes the energy management results with the two investigated frameworks, centralized and decentralized EC operation. Fig. 4 displays the results regarding the individual (Fig. 4(a)) and collective (Fig. 4 (b)) power flow. It shows the energy exchanges on a typical day. At every time step, the positive values represent the share of community energy between the different users $P^{g-}_{n,t}$. The negative values display the contribution of each producer (i.e., the physical export $P^{g+}_{n,t}$).

Fig. 4 (a) illustrates the power flow of each member (i.e., at the meter level) for both centralized and decentralized frameworks. Note that users 1, 3, 5, and 7 primarily consume power, while users 2, 4, and 6 mainly produce electricity on the sample day.

Fig. 4 (b) shows the net power flow at the community level, i.e., energy imported/exported from/to the grid and the community and the total EC costs are displayed in the coloured boxes as CC^{*} for the centralized framework and $\sum_{n \in N} CI^{*}_{n}$ for the decentralized framework. The main difference between decentralized and centralized frameworks is that in the centralized case, the community exchanges less energy with the grid (i.e., increased collective self-consumption). The total energy community bill using the centralized framework renders the most significant savings (26.87 %) compared to the decentralized framework. However, users deviate from their optimum.

3.3. Settlement results

The frameworks in the operational stage are tested over a month in an offline mode with deterministic profiles. The baseline is calculated with the outcome of the operational stage and individual bills considering the grid prices only (i.e., no community and energy exchanges).

The optimal EC bill CC^{*} is also computed thanks to centralized management. Ultimately, from the operational stage, the time-series profiles at the user's meters are available and further used in the settlement phase in a postdelivery fashion. The users will be subject to different final bills, which highly depend on the applied allocation method.

3.3.1. Centralized settlement: costs allocation

This section examines various cost allocation methods for the centralized framework, as discussed in Section 2.3.2 [46]. Fig. 5 illustrates the individual's bill savings achieved through different approaches. Fig. 5(a) depicts the revenues of "net consumers," while Fig. 5 (b) displays the revenues of "net producers."

The Shapley value determines the marginal contributions of the individuals, rendering the "fairest" cost allocation. However, the operational stage must be calculated for all possible combinations of the subcoalitions of the EC. Unlike the Shapley value, the equal allocation of non-separable values (EANSV) approach is directly computed with the outcome of the operational stage. Hence, while it offers similar results to the Shapley value, it is computationally fast.

The optimization-based method (OPT) offers a "flexible" approach,

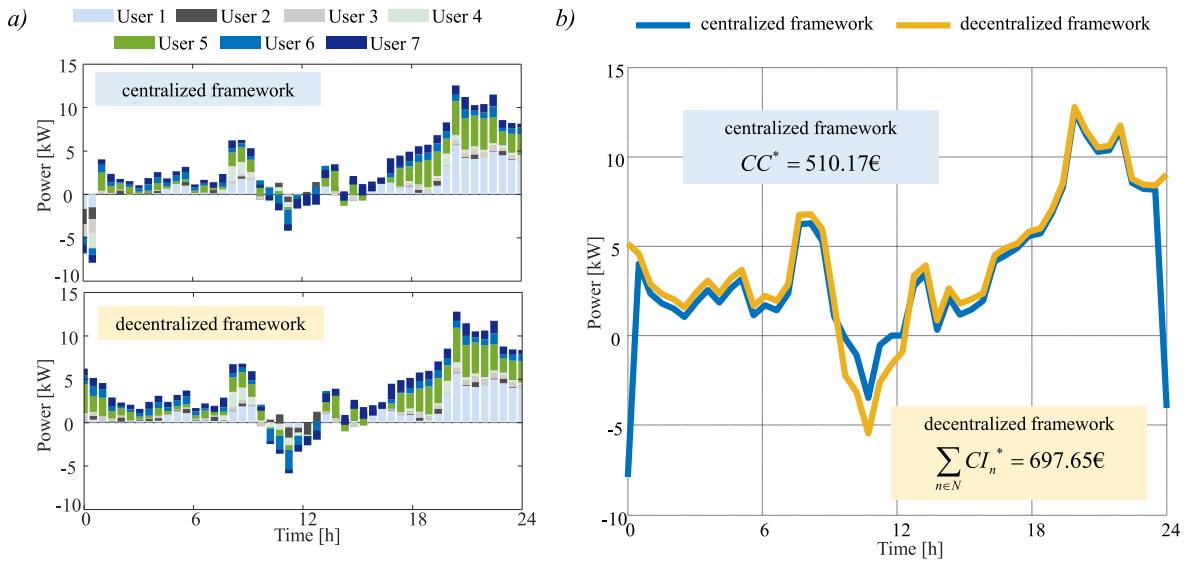

Fig. 4. Power exchange in the community for a sample day comparing centralized and decentralized frameworks in the operational stage.

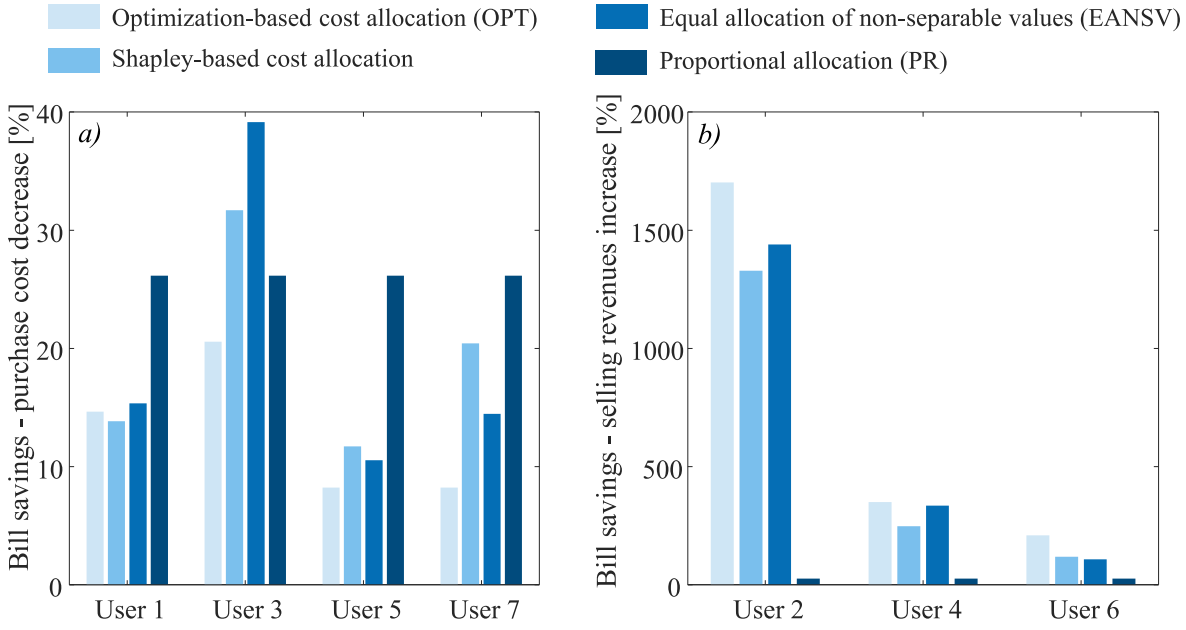

Fig. 5. Individual bill savings through various cost-allocation methods.

allowing the incorporation of additional features into the model, such as the user's preferences for willingness to pay more [46]. In general, it yields advantages for all members of the EC, particularly benefiting prosumers who exclusively export. This encourages locally generated renewable energy while preventing net consumers from increasing their bills. As depicted in Fig. 7, the OPT method provides results comparable to Shapley and EANSV. It is noteworthy that with this optimization method, users receive an internal EC price, which is more favorable than the typical price with the retailer.

Finally, the proportional (PR) bill allocation gives all users an identical bill increase. It may not be favorable for prosumers who solely export, as their revenues will be equivalent to their peers. In the PR approach, the marginal contributions of each user are not considered, making it more egalitarian but not genuinely fair. This approach could indirectly motivate prosumers to leave the EC and do business independently (e.g., by participating in the local energy market).

Overall, prosumers tend to derive more benefits than consumers, as depicted in Fig. 5. Except for the proportional allocation method, all other approaches result in higher revenues.

3.3.2. *Decentralized settlement: post-delivery markets*

Users can trade within the energy community in the decentralized framework following the individual operations. Consequently, this section delves into the outcomes of employing diverse bidding strategies in two clearing mechanisms (peer-to-peer and pool) as described in the preceding sections. This leads to six possible configurations, two market mechanisms, and three bidding strategies.

Fig. 6 displays the bidding strategies considered in this analysis. The constant bids (BS2) are represented by triangles, as an average between the retail selling and purchasing prices. Similarly, the BS3 shows the proportionality between the bid and the net power, increasing for larger absolute values of the power, see the squares in Fig. 6. Fig. 6(a) shows User 5 as a net consumer and Fig. 6(b) depicts User 2 as a net producer. Finally, the BS1 displays random values between the retail purchasing

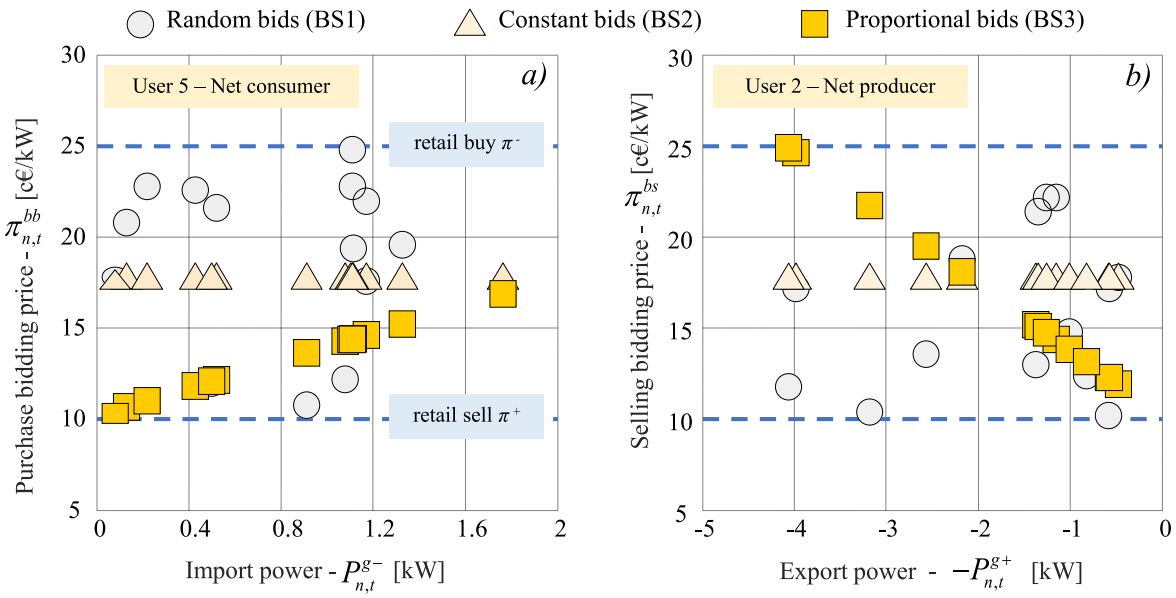

Fig. 6. Bidding strategies for consumers and producers.

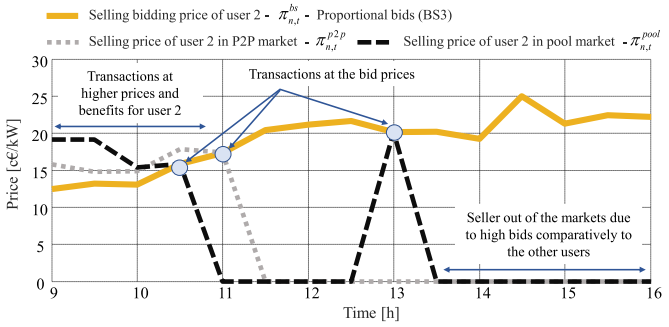

Fig. 7. Comparison of a bidding price vs actual price in the market for User 2 on a typical day.

and selling prices.

Table 3 shows the results corresponding to the overall monthly bill of the EC of the use case. All scenarios are compared to the baseline, corresponding to the initial bill, calculated from the individual operation charged at retailer prices – an overall baseline community bill of 697.65 €. The results show that the constant bidding strategy (BS2) provides the most significant bill decrease for both pool and P2P market clearing mechanisms. It represents a reduction of 12.98 % when implementing the pool mechanism and 9.04 % when using a P2P mechanism. This can be attributed to both prosumers and consumers placing bids at identical prices. Nevertheless, the underlying cause is that the random (BS1) and proportional (BS3) bidding strategies may never lead to actual transactions.

For additional analysis, Fig. 7 shows the selling prices for a typical day for User 2 within the market-based settlement. In this case, User 2 acts as a prosumer, and during sunny hours, the displayed bidding price is proportional to the generated power (BS3). However, as previously indicated, although the bid is proportional to the power, it often does not translate into actual transactions. It is crucial to emphasize that when the proposed bidding strategy is not accepted in the market, the power is traded at retailer prices.

Likewise, a comparison of the monthly bills for the EC members is depicted in Fig. 8, which shows the bill savings for the bidding strategies and market clearing mechanisms presented in Section 2.4.2. It is visible that participating in the market yields benefits for all members under any of the bidding strategies, especially for net consumers, considering that the purchase price with the retailer is significantly higher than the price at which they sell, inherently resulting in higher costs.

Additionally, for all investigated bidding strategies, P2P performs less favorably than the pool market mechanism. Indeed, conducting individual trades without knowledge of the bid offers at better prices diminishes the potential for higher profits. Conversely, it is advantageous to adopt a bidding strategy where all members converge around the average price between the initial selling and purchasing prices of the retailer. This bidding strategy (BS2) proves to be beneficial for all users; prosumers can sell at a higher price, while consumers can purchase at a reduced cost compared to the typical retail price (for both P2P and Uniform clearing mechanisms). Moreover, the uniform clearing mechanism ensures that all users receive an identical price, resulting in uniform and lower prices for all members. In instances where free competition might limit opportunities for trading, assuming that all users bid and ask for roughly the same price, enables them to approach the average price, providing some assurance of reducing their bills or increasing their earnings.

Table 3
Overall EC bill (€) and savings (%) compared to baseline with different bidding strategies and clearing mechanisms.

	P2P Market	Pool Market
Random bids (BS1)	656.53 (– 6 %)	637.72 (– 9 %)
Constant bids (BS2)	634.57 (– 9 %)	607.10 (– 13 %)
Proportional bids (BS3)	652.92 (– 6 %)	639.06 (– 8 %)

3.4. Fairness assessment

Determining the best approach for each member of the EC poses a challenge, considering their individual contributions and personalized interests. It mainly involves considering their freedom in selecting trading partners and the flexibility to adapt and modify their bidding strategy over time.

To assess the cost allocation methods outlined in Section 3.3 beyond their financial dimension, this study seeks to understand how each proposed approach can ensure a fair distribution for any member of the EC.

A fair allocation involves motivating users to participate in the EC without requiring time-consuming actions or intricate account

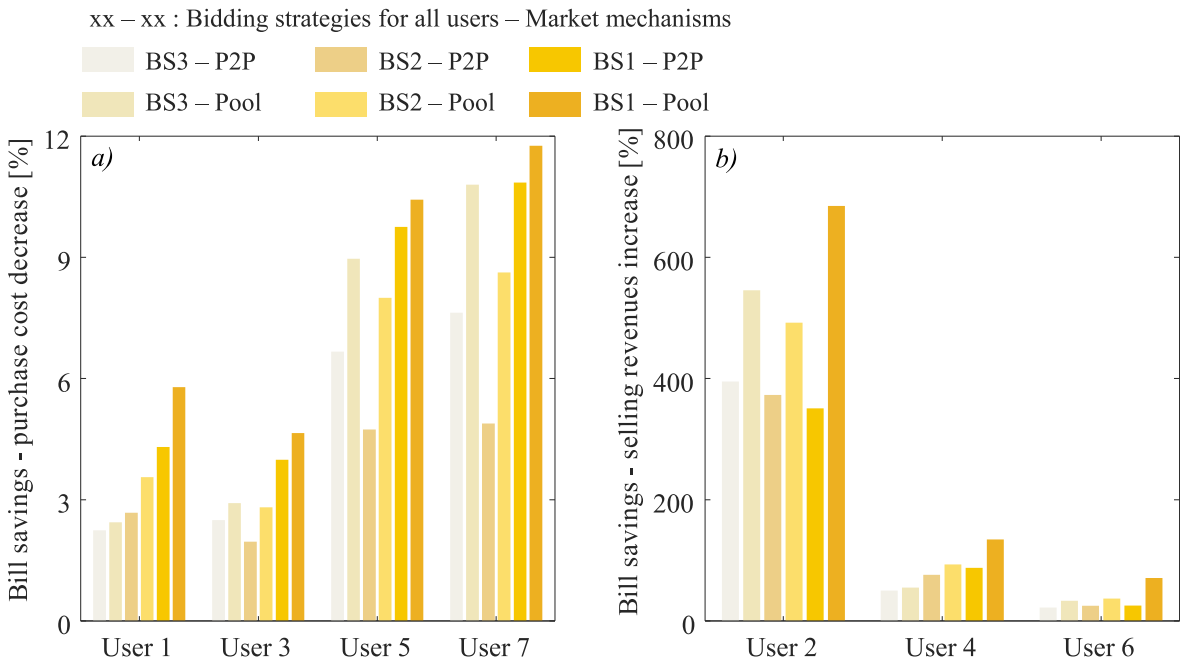

Fig. 8. Monthly bill savings: A comparison of bidding strategies using P2P and Pool clearing mechanisms.

management based on individual preferences. It also includes considerations such as supporting the least advantaged user or expressing a willingness to pay more for renewable energy while fostering collaboration rather than competition in the local energy market. To be able to compare the proposed method from the fairness perspective, this work uses the metrics mentioned in Section 2.2.

Table 4 shows the outcomes following the application of the Jain, MinMax, QoE indexes and the distance (Δ) index to both the centralized and decentralized frameworks. Note that all indexes close to 100 % indicate a more fair billing system [41].

As for the Jain and MinMax indexes, they assign a 100 % fairness score to the proportional (PR) ruled-based cost allocation, rendering it a method regarded as totally fair. In contrast, both indexes convey that the other methods fall short, registering below 30 % and being labeled "unfair." Similarly, in the MinMax index, since all methods are calculated using bill savings, the PR approach is the only method to achieve 100 % equal repartition. In contrast, the other methods fail to achieve a high fairness performance, since the difference in bill savings among users is considerable. As for the quality of experience index (QoE), all assessed methods produce similar results, with the PR approach slightly outperforming the others. These results confirm the findings in [15].

It is essential to highlight that the Jain, MinMax, QoE indexes may not be suitable for assessing the fairness of an allocation method in the context of energy communities, particularly when considering the Shapley value costs allocation approach, which is undervalued by these metrics.

Regarding the Δ index, it is important to note that it compares any method to one that is considered as fair. In this research, the reference method corresponds to the Shapley value, making it impossible to assess. In this context, a lower value indicates a "fairer billing," implying that the evaluated method is closer to the Shapley value. Evidently, the Δ method gives 100 % for the Shapley value in Table 4.

Notice that although the PR benefit allocation method has a Jain index of 100 %, it gives the worst Δ index, according to Ref. [41], from all analyzed methods. Moreover, from the decentralized methods, the Pool-BS2 method provides the best performance in both indexes, contrary to the results shown in Fig. 8. This poses the BS1-Pool as the best bill decrease for the decentralized approaches.

Table 4 highlights that the best fairness index combination is provided by the EANSV method, rendering the best combination of Δ and Jain index compared to all analyzed methods. However, as previously discussed, the EANSV allocation method might not be desirable for net producers and could discourage them from participating in EC when engaging prosumers is crucial. It is also essential to recognize the benefits that being part of an EC can bring to other community members.

Furthermore, the optimization method aligns with both fairness indexes under similar circumstances much like the Shapley value and EANSV, which are already recognized as "fairer" approaches. Moreover, as shown in Fig. 5, the optimization-based method provides a higher bill decrease, especially benefiting prosumers aiming to boost their profits.

3.5. Discussion and future work

Understanding that the findings are sensitive to user assets and profile changes is essential. Altering the study case and inputs may significantly impact the outcomes. The study underscores that existing fairness indexes do not adequately represent fairness. Nevertheless, the same conclusions apply to other types of ECs with diverse user types. The importance of accurately measuring fairness in ECs should be crystal clear to all stakeholders. When evaluating fairness indicators, it is

Table 4
Comparison of billing allocations with four fairness indexes.

	Decentralized framework						Centralized framework			
	P2P-BS3	P2P-BS2	P2P-BS1	Pool-BS3	Pool-BS2	Pool-BS1	Shapley	EANSV	PR	OPT
Jain index	21.21 %	26.36 %	23.42 %	20.38 %	24.73 %	23.57 %	24.37 %	25.01 %	100 %	24.94 %
MinMax	0.57 %	1.14 %	0.53 %	0.42 %	0.68 %	0.57 %	0.88 %	0.73 %	100 %	0.48 %
QoE	63.21 %	63.35 %	63.26 %	63.17 %	63.46 %	63.35 %	63.40 %	63.32 %	67.28 %	63.45 %
Δ	76.40 %	77.51 %	76.68 %	78.40 %	83.94 %	78.98 %	100 %	93.43 %	73.05 %	84.68 %

crucial to identify simple and practical cost allocation methods, as testing a wide range of repartition keys (KoR) can be practically infinite. This includes using Shapley value approximations and other complex repartition keys. Furthermore, this work dealt with operational frameworks, future work may include investment decisions to consider within the fairness assessment.

Based on the analyzed cases, the centralized framework consistently offers significant bill savings and fairer allocation approaches compared to the decentralized framework. Additionally, in the assessed methods, the users who experienced the greatest overall benefit were the prosumers, enjoying more important bill savings in all tested strategies. Nevertheless, additional types of comparisons could also be explored within the same framework, for instance, contrasting market-based and KoR within centralized frameworks, particularly for evaluating metrics beyond economic metrics.

Moreover, the market-based mechanisms present significant potential for improvement. Bidding strategies play a significant role in decentralized frameworks with market-based allocation. As demonstrated in this research, analyzing actual transactions is crucial as they substantially impact results. Overall, the pool market mechanism demonstrated superior bill savings compared to P2P. The fairness indexes were generally similar for the decentralized framework approaches, with the Pool-BS2 case particularly interesting for the members of the EC. Additionally, it is important to emphasize that the market in decentralized frameworks may not be advantageous in a small energy community with a mix of users who either consume or produce simultaneously and lack potential buyers. A more balanced composition is necessary, explaining the limited bill reduction observed when implementing P2P or pool market mechanisms. Since economic efficiency of a market design highly depends on available quantities (i.e., power) rather than bid/ask prices.

Additionally, there is a need for more thorough exploration of bidding strategies within a decentralized framework to improve the process. This entails examining various assumptions related to bidding strategies and devising an optimal model. However, for local energy markets, it is essential to consider the active involvement of users in the market—engaging with their preferences and trading with others. Typically, in simulation, it is considered that participants actively bid. However, in reality, user participation might not be as active as expected despite a significant initial interest. Ultimately, their actions may not be accurately reflected in real-world experiments. A recent study in Winkel, Switzerland, where 159 participants were bidding in a local energy market from June 2022 to March 2023, revealed that while users express a willingness to engage in renewable energy projects, they exhibit limited activity in adjusting their parameters, such as bidding prices [47]. Fig. 9 displays the user's engagement with the device to change parameters and actively participate in the local energy market by setting different prices of electricity. Fig. 9(a) shows the probability distribution of the users' average activity during the analyzed period. Fig. 9(b) displays the number of active users after the first day of connection (active refers to the change of any parameter in the device).

The results show that less than 5 % of the users were engaged in changing parameters or simply checking the behavior of their activity in the local energy market. Likewise, at least 95 % of the user sample dedicated time on the initial day and subsequently maintained their parameters for the duration of the project. This issue has been also discussed in Ref. [33].

Furthermore, it is essential for future research to incorporate grid fees and consider the grid network to facilitate a more precise comparison. Our analysis lacks consideration of grid fees and the grid network, thereby significantly impacting the outcomes. It is important to note that our assumption is based on the concept that energy can be shared among users within centralized frameworks, and consequently, the energy at the community level will be billed at retail prices. Additional work needs to be conducted to compare community-based P2P and uniform market mechanisms when the ratio between the prosumers and the consumers is largely in favor of the prosumers. A higher self-consumption ratio could also impact DSO grid tariffs and limit energy communities' development.

4. Conclusions

A two-stage method is implemented for the operation and benefit allocation of an energy community (EC), considering various strategies within centralized and decentralized frameworks, focused on economic and fairness-oriented criteria. The first stage consists of either a centralized or an individual operation of the physical flows in the EC. The second stage allows a comparison of a-posteriori market designs with various collective cost allocation to share the benefits among the members of the EC. For the market-based settlement, three bidding strategies are proposed to assess the performance of the decentralized framework, applying two mechanisms to define the market (peer-to-peer, and pool). This leads to six possible configurations, two market mechanisms, and three bidding strategies.

Moreover, four approaches are tested for cost allocation in the centralized framework. The *equal allocation of non-separable values* allocation method renders the most straightforward and fairer cost allocation. Nevertheless, there is an increasing interest in incorporating additional features like end-user preferences. In that case, the proposed optimization-based allocation method provides the most balanced tradeoff among the analyzed methods regarding financial and fairness concerns. Additionally, regardless of the allocation method, the centralized framework provides 15.96% higher bill savings at the community level compared to the average bidding strategy (BS2) with

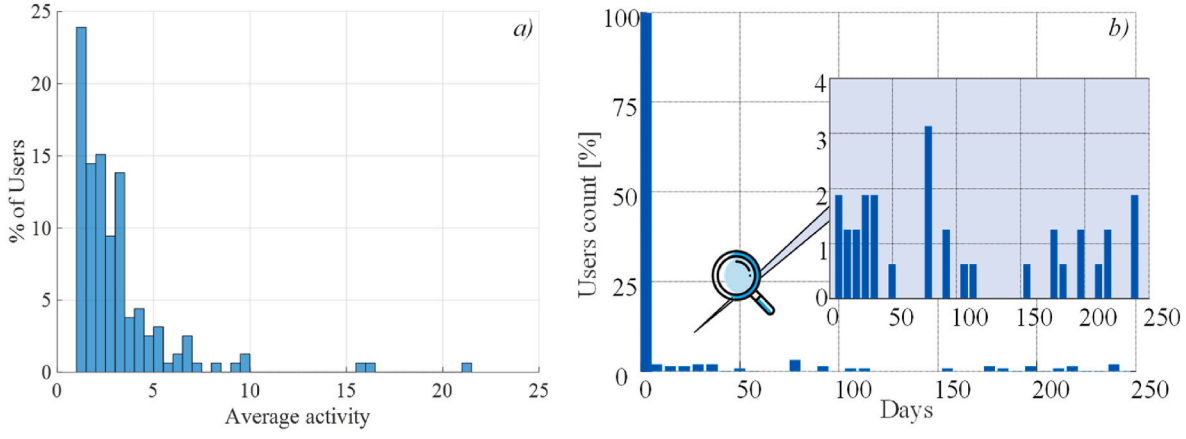

Fig. 9. User's activity (clicks) on the device to participate in a program for willingness to pay more [47].

the pool market in the decentralized approach, which showed the best performance of the decentralized framework overall.

In the decentralized framework, the pool market systematically returns considerable savings. The results show that the BS2 gives the most significant bill decrease among the decentralized framework for both pool and P2P market mechanisms. It conveys a reduction of 12.98 % when implementing the pool mechanism and 9.04 % when using a P2P mechanism, compared to the baseline, corresponding to the initial bill, calculated from the individual operation charged at retailer prices.

Furthermore, this study introduces a discussion on fairness indexes, which compares a market-based decentralized approach with centrally managed ECs. It demonstrates that fairness metrics derived from other fields are being applied indiscriminately to ECs' context. However, it is essential to highlight that measuring fairness in ECs is not straightforward from an engineering and mathematical perspective due to its highly subjective nature. Assessing a method using inaccurate definitions from other fields may cause unfair cost allocation. Moreover, diverse factors influence fairness estimation, including investment, assets ownership, user types, operational decisions, and cost allocation methods.

CRediT authorship contribution statement

María-Victoria Gasca: Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Remy Rigo-Mariani:** Conceptualization, Validation, Formal analysis, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Vincent Debusschere:** Conceptualization, Formal analysis, Writing – review & editing, Supervision, Project administration. **Yousra Sidqi:** Conceptualization, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Maria-Victoria Gasca reports financial support was provided by French National Research Agency. Yousra Sidqi reports financial support was provided by Innosuisse Swiss Innovation Agency. Remy Rigo-Mariani reports article publishing charges and travel were provided by French National Research Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

References

[1] Energy communities." Accessed: Nov. 06, 2023. [Online]. Available: https://energy.ec.europa.eu/topics/markets-and-consumers/energy-communities_en#citizens-and-renewable-energy-communities.
[2] Wierling A, et al. A Europe-wide inventory of citizen-led energy action with data from 29 countries and over 10000 initiatives. Nature Scientific Data Dec. 2023;10 (1). https://doi.org/10.1038/s41597-022-01902-5.
[3] French Government. Ordinance no. 2016-1019 of july 27, 2016 related to selfconsumption of electricity (in french, original title: "'ordonnance no 2016-1019 du 27 juillet 2016 relative à l'autoconsommation d'electricité"').Accessed: Nov. 21, 2023. [Online]. Available: https://www.legifrance.gouv.fr/loda/id/JORFTEXT000032938257.
[4] Norbu S, Couraud B, Robu V, Andoni M, Flynn D. Modeling economic sharing of joint assets in community energy projects under LV network constraints. IEEE Access 2021;9:112019–42. https://doi.org/10.1109/ACCESS.2021.3103480.
[5] Saif A, Khadem SK, Conlon M, Norton B. Impact of distributed energy resources in smart homes and community-based electricity market. IEEE Trans Ind Appl 2022. https://doi.org/10.1109/TIA.2022.3202756.
[6] Putratama MA, Rigo-Mariani R, Mustika AD, Debusschere V, Pachurka A, Besanger Y. A three-stage strategy with settlement for an energy community management under grid constraints. IEEE Trans Smart Grid 2022;3053(c):1–10. https://doi.org/10.1109/TSG.2022.3167862.
[7] Hupez M, Toubeau J-F, Atzeni I, De Greve Z, Vallee F. Pricing electricity in residential communities using game-theoretical billings. IEEE Trans Smart Grid 2022. https://doi.org/10.1109/tsg.2022.3206912. 1–1.
[8] Coignard J, Rigo-Mariani R, Debusschere V. Individual and collective objectives in an energy community with network constraints. Sustain Cities Soc 2024;101: 105083. https://doi.org/10.1016/j.scs.2023.105083.
[9] Li N, Hakvoort RA, Lukszo Z. Cost allocation in integrated community energy systems - a review. Elsevier Ltd.; Jul. 01, 2021. https://doi.org/10.1016/j.rser.2021.111001.
[10] Mustika AD, Rigo-Mariani R, Debusschere V, Pachurka A. A two-stage management strategy for the optimal operation and billing in an energy community with collective self-consumption. Appl Energy 2022;310(February):118484. https://doi.org/10.1016/j.apenergy.2021.118484.
[11] Silva R, Faria S, Moreno A, Retorta F, Mello J, Villar J. Impact of transaction pricing mechanisms on energy community benefits sharing. In: International conference on the European energy market, EEM. IEEE Computer Society; 2023. https://doi.org/10.1109/EEM58374.2023.10161899.
[12] Liu C, Li Z. Comparison of centralized and peer-to-peer decentralized market designs for community markets. IEEE Transac. Ind. Applic. Jan.-Feb. 2022;58(1): 67–77. https://doi.org/10.1109/TIA.2021.3119559.
[13] Mello J, de Lorenzo C, Campos FA, Villar J. Pricing and simulating energy transactions in energy communities. MDPI; Feb. 01, 2023. https://doi.org/10.3390/en16041949.
[14] Sousa T, Soares T, Pinson P, Moret F, Baroche T, Sorin E. Peer-to-peer and community-based markets: a comprehensive review. Elsevier Ltd.; Apr. 01, 2019. https://doi.org/10.1016/j.rser.2019.01.036.
[15] Faria AS, et al. P2P market coordination methodologies with distribution grid management. Sustainable Energy, Grids and Networks 2023;34(Jun). https://doi.org/10.1016/j.segan.2023.101075.
[16] Capper T, et al. Peer-to-peer, community self-consumption, and transactive energy: a systematic literature review of local energy market models. Elsevier Ltd.; Jul. 01, 2022. https://doi.org/10.1016/j.rser.2022.112403.
[17] Okwuibe GC, Wadhwa M, Brenner T, Tzscheutschler P, Hamacher T. Intelligent bidding strategies in local electricity markets: a simulation-based analysis. In: 2020 IEEE electric power and energy conference, EPEC 2020. Institute of Electrical and Electronics Engineers Inc.; Nov. 2020. https://doi.org/10.1109/EPEC48502.2020.9320067.
[18] Wang Y, Yang Q, Zhou Y, Zheng Y. A risk-averse day-ahead bidding strategy of transactive energy sharing microgrids with data-driven chance constraints. Appl Energy 2024;353(Jan). https://doi.org/10.1016/j.apenergy.2023.122093.
[19] Heilmann J, Wensaas M, Crespo del Granado P, Hashemipour N. Trading algorithms to represent the wholesale market of energy communities in Norway and England. Renew Energy Nov. 2022;200:1426–37. https://doi.org/10.1016/j.renene.2022.10.028.
[20] Mengelkamp E, Staudt P, Garttner J, Weinhardt C. Trading on local energy markets: a comparison of market designs and bidding strategies. In: 14th international conference on the European energy market (EEM); 2017.
[21] Houwing M, Dukovska I, Paterakis NG. A reputation management system for the fair utilization of community energy storage systems. IEEE Trans Smart Grid Jan. 2023;14(1):582–92. https://doi.org/10.1109/TSG.2022.3197355.
[22] Kulmala A, Baranauskas M, Safdarian A, Valta J, Jarventausta P, Bjorkqvist T. Comparing value sharing methods for different types of energy communities. In: Proceedings of 2021 IEEE PES innovative Smart grid technologies Europe: Smart grids: toward a carbon-free future, ISGT Europe 2021. Institute of Electrical and Electronics Engineers Inc.; 2021. https://doi.org/10.1109/ISGTEurope52324.2021.9640205.
[23] Jain R, Chiu D-M, Hawe WR. A quantitative measure of fairness and discrimination for resource allocation. In: Shared computer systems. DEC Research Report TR-301; 1984.
[24] Perger T. Fair energy sharing in local communities:dynamic participation of prosumers. In: 2020 17th international conference on the European energy market (EEM); 2020.
[25] Moret F, Pinson P. Energy collectives: a community and fairness based approach to future electricity markets. IEEE Trans Power Syst Sep. 2019;34(5):3994–4004. https://doi.org/10.1109/TPWRS.2018.2808961.
[26] Hobfeld T, Skorin-Kapov L, Heegaard PE, Varela M. Definition of QoE fairness in shared systems. IEEE Commun Lett Jan. 2017;21(1):184–7. https://doi.org/10.1109/LCOMM.2016.2616342.
[27] Cremers S, Robu V, Zhang P, Andoni M, Norbu S, Flynn D. Efficient methods for approximating the Shapley value for asset sharing in energy communities. Appl Energy 2022;(331). https://doi.org/10.1016/j.apenergy.2022.120328.

[28] Yokote K, Funaki Y, Kamijo Y. A new basis and the Shapley value. Math Soc Sci 2016;80:21–4. https://doi.org/10.1016/j.mathsocsci.2015.12.003.
[29] Yang Y, Hu G, Spanos CJ. Optimal sharing and fair cost allocation of community energy storage. IEEE Trans Smart Grid Sep. 2021;12(5):4185–94. https://doi.org/10.1109/TSG.2021.3083882.
[30] Casalicchio V, Manzolini G, Prina MG, Moser D. From investment optimization to fair benefit distribution in renewable energy community modelling. Appl Energy 2022;310(Mar). https://doi.org/10.1016/j.apenergy.2021.118447.
[31] Li N, Hakvoort RA, Lukszo Z. Cost allocation in integrated community energy systems — performance assessment. Appl Energy 2022;307(Feb). https://doi.org/10.1016/j.apenergy.2021.118155.
[32] Lan Tian, David Kao, Mung Chiang, Ashutosh Sabharwal. An axiomatic theory of fairness in network resource allocation. In: *2010 proceedings IEEE INFOCOM*, IEEE xplore; 2010. p. 1–9.
[33] Roberts MB, Sharma A, MacGill I. Efficient, effective and fair allocation of costs and benefits in residential energy communities deploying shared photovoltaics. Appl Energy 2022;305(Jan). https://doi.org/10.1016/j.apenergy.2021.117935.
[34] Varian HR. "Two problems in the theory of fairness," J public econ. 1976. April–May.
[35] Long C, Zhou Y, Wu J. A game theoretic approach for peer to peer energy trading. Energy Proc Feb. 2019;159:454–9. https://doi.org/10.1016/J.EGYPRO.2018.12.075.
[36] Hupez M, Toubeau JF, De Greve Z, Vallee F. A new cooperative framework for a fair and cost-optimal allocation of resources within a low voltage electricity community. IEEE Trans Smart Grid 2021;12(3):2201–11. https://doi.org/10.1109/TSG.2020.3040086.
[37] Rocha R, et al. A three-stage model to manage energy communities, share benefits and provide local grid services. Energies Feb. 2023;16(3). https://doi.org/10.3390/en16031143.
[38] Chis A, Koivunen V. Coalitional game-based cost optimization of energy portfolio in smart grid communities. IEEE Trans Smart Grid Mar. 2019;10(2):1960–70. https://doi.org/10.1109/TSG.2017.2784902.
[39] Fioriti D, Frangioni A, Poli D. Optimal sizing of energy communities with fair revenue sharing and exit clauses: value, role and business model of aggregators and users. Appl Energy 2021. https://doi.org/10.1016/j.apenergy.2021.117328.
[40] Köppen M, Ohnishi K, Tsuru M. Multi-jain fairness index of per-entity allocation features for fair and efficient allocation of network resources. In: Proceedings - 5th international conference on intelligent networking and collaborative systems, INCoS 2013; 2013. p. 841–6. https://doi.org/10.1109/INCoS.2013.161.
[41] Baharlouei Z, Hashemi M, Narimani H, Mohsenian-Rad H. Achieving optimality and fairness in autonomous demand response: benchmarks and billing mechanisms. IEEE Trans Smart Grid 2013;4(2):968–75. https://doi.org/10.1109/TSG.2012.2228241.
[42] Golla A, Röhrig N, Staudt P, Weinhardt C. Evaluating the impact of regulation on the path of electrification in Citizen Energy Communities with prosumer investment. Appl Energy 2022;319:119241. https://doi.org/10.1016/j.apenergy.2022.119241. April 2021.
[43] Lin J, Pipattanasomporn M, Rahman S. Comparative analysis of auction mechanisms and bidding strategies for P2P solar transactive energy markets. Appl Energy Dec. 2019;255. https://doi.org/10.1016/j.apenergy.2019.113687.
[44] Blouin MR, Serrano R. A decentralized market with common values uncertainty: non-steady states. Rev Econ Stud Apr. 2001;68(2):323–46. https://doi.org/10.1111/1467-937X.00171.
[45] Kiedanski D, Kofman D, Horta J. PyMarket - a simple library for simulating markets in Python. J Open Source Softw Feb. 2020;5(46):1591. https://doi.org/10.21105/JOSS.01591.
[46] Gasca MV, Rigo-Mariani R, Debusschere V, Sidqi Y, Clastres C. Costs allocation in energy communities: an insight on users' preferences. In: IEEE PES innovative Smart grid technologies conference Europe. IEEE Computer Society; 2023. https://doi.org/10.1109/ISGTEUROPE56780.2023.10408102.
[47] EKZ. Solarstrom von Nachbars Dach kaufen [Online]. Available: https://www.ekz.ch/de/blue/innovation/2021/ortsnetz-winkel.html. [Accessed 22 December 2023].