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Pricing and sharing rules for energy communities[☆]

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ABSTRACT

Prosumers and consumers can form together a renewable energy community. The community purchases the production surplus from prosumers and resells it to members and energy retailers. Members buy electricity at a discount compared to the retail price, and prosumers sell their electricity at a premium compared to the market price. The community determines these internal prices and establishes a sharing rule to allocate collective self-consumption among its members. In this paper, we analyze the roles of prices and sharing rules in identifying feasible communities and the resulting allocation of surplus among members. We illustrate our results with a numerical simulation.

1. Introduction

Since the last decades, the global energy landscape has been witnessing significant transformations, with a growing implication of non-classic and decentralized actors and a growing participation of citizens as actors in the energy transition (Caramizaru and Uihlein, 2020; Kolesar, 2022; Hanke et al., 2021; Hvelplund, 2006; Gui and MacGill, 2018). The objective is to empower citizens so that they can actively contribute to the energy transition, both individually and collectively. Individual participation takes the form of investment in renewable energy technologies at residences or workplaces, such as installing solar panels, adopting energy-efficient appliances, or modifying consumption behavior (Gautier et al., 2019). Collective participation involves collaboration among multiple individuals to pool resources, expertise, and aspirations for renewable energy initiatives (Rossetto et al., 2022). For instance, citizens may come together to finance and install wind farms, hydroelectric plants, or community solar installations to produce energy for their own use.

The concept of energy community has various interpretations and understandings, reflecting its multifaceted nature and meanings (Walker and Devine-Wright, 2008; Bauwens et al., 2022). Collective citizen participation is not a novelty for countries like Denmark (Mey and Diesendorf, 2018) or Germany (Spasova and Braungardt, 2022); the magnitude of implementation of such participation varies across regions (Lelieveldt and Schram, 2023). It, however, has gained importance in the European Union's policy agenda with the "Clean Energy for all Europeans" initiative and the Renewable Energy Directive ('RED II') adopted in 2018. The RED II introduces the concept of Renewable Energy Communities (REComs) to encourage the participation of new stakeholders, including citizens, private companies, and public organizations.

A RECom is defined as *"a legal entity which, in accordance with the applicable national law, is based on open and voluntary participation, is autonomous and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that entity"* (The European Parliament and the Council of the European Union, 2018). A RECom can carry out various activities, such as energy generation and consumption, storage, sharing, flexibility, management, and trading (Rossetto et al., 2022), within a local perimeter. We focus on communities that produce, share, and consume energy collectively, also known as *collective-self-consumption* activities or energy-sharing communities (Rossetto et al., 2022).

Gautier et al. (2025) investigated the dynamics of interactions between REComs and the energy system, as well as their potential to reduce the overall cost of the energy system. They show that REComs are profitable for participants and welfare-improving if a minimum amount of the energy produced within the RECom is self-consumed inside the community. Renewable energy communities create value by self-consuming in the neighborhood what they produce.

However, creating value is only one side of the coin. Participants may have different motivations to join a community: environmental concern, community identity, social norms, etc. (Kalkbrenner and Roosen, 2016; Soeiro and Ferreira Dias, 2020; Süsser et al., 2022;

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Magnusson and Palm, 2019) but economic benefits are recognized to play a key role (Fina et al., 2019). An important issue for the implementation of a community is, therefore, to share the value created among the participants. The repartition of value should reflect both the objectives of the community, such as social inclusion, a preference for redistributive justice (Hanke and Lowitzsch, 2020) or environmental concerns and as well as the necessity of achieving a stable and mutually beneficial allocation among members. Gautier et al. (2025) show that the two dimensions can be dissociated. The community value is independent of its internal organization, which matters only for the repartition of the value among the members. In this paper, we will use numerical simulations to illustrate the feasible and infeasible sharing rules and the resulting allocation of surplus among members.

In the literature, several authors have proposed mechanisms to share value within the community. Mustika et al. (2022) propose several key factors for allocating the collective self-consumed electricity among members. These key approaches include static schemes, pro-rata methods, cooperative game theory, and optimization-based strategies. The static key allocates energy equally among members, while the pro-rata key distributes energy based on consumption, production, or investment levels. The Shapley value method computes the marginal contributions of each member, while the minimization of the collective bill and equal bill-saving ratios are optimization-based approaches.

Analyzing a collective self-consumption operation in a multi-energy microgrid environment, Roy et al. (2023) favor the profitability of investments to determine a sharing rule. In their model, the REComanager allocates energy to consumers with the highest willingness to pay. Even though such a repartition key can be optimal in an industrial context, it may not be the case when other motivations, such as those beyond the return on investment, are considered. Fina et al. (2022) demonstrate that dynamic allocation, which allocates energy to ensure optimal usage of production assets, yields a significantly higher collective benefit compared to static allocation, where available electricity is equally distributed among community members. Their analysis reveals that the dynamic allocation method leads to greater self-consumption, thereby yielding higher financial benefits for the energy community. Based on an analysis of 71 cases, Hanke et al. (2021) demonstrate that communities frequently fail to redistribute benefits to the most vulnerable groups of participants, resulting in their underrepresentation within the communities. Other authors (Abada et al., 2020a,b; Moncecchi et al., 2020) have examined game theory-based methods for allocating energy or energy-related benefits to RECom members. They RECommend using sophisticated mechanisms, such as the Shapley value, to share benefits among members, as simple sharing rules may lead to unstable community configurations.

By contrast, regulators and RECom managers often propose simple sharing rules, such as per-capita or pro-rata consumption, to allocate energy among members because they are easily understood by members and their implementation is not overly complex.

Finally, the question of sharing value within a community has been examined in other contexts, notably within the framework of common-pool resources (Ouvrard et al., 2022; McCay et al., 2014; Cronkleton et al., 2012). Often, there is a tension between an egalitarian allocation of benefits and one based on usage.

In this paper, we examine the issue of sharing value within a community comprising prosumers and consumers. Prosumers sell their production surplus to the community, which stores it or resells it to members or external retailers. To become a member, prosumers and consumers must pay an entry fee to finance the community's assets, such as a battery in our example, and the associated management costs. Members can then buy electricity at a discount compared to the retail price, and prosumers can sell their electricity at a premium compared to the market price.

The community creates value by collectively consuming the electricity surplus purchased from prosumers, and the community invests in a battery to maximize collective self-consumption. To share the value it creates, the community has two instruments: the internal prices for electricity and the sharing rule. The sharing rule allocates the collectively consumed electricity to each member; the prices transform electricity lows into value. Together, these two instruments influence the redistribution of benefits within the community.

We first identify the prices and sharing rules that are feasible within a community. A viable community should collectively create enough value and distribute it in a way that ensures each member benefits from being part of the community. For this, we utilize data from a virtual energy community in Belgium. In our simulations, we compare two main categories of sharing rules: an egalitarian rule (per-capita) and a proportional to consumption. In each case, the rule can be applied in almost continuous time (every 15 min) on a more aggregated period (1 year in our example). Our examples demonstrate that it is not always possible to find prices that benefit all individuals within the community, particularly with pro-rata sharing rules. Finally, we demonstrate that even with an egalitarian rule, the resulting allocation of benefits is not necessarily egalitarian, as several constraints must be taken into account. To summarize, our results suggest that it is not always possible to achieve an equal distribution of value and that pro-rata sharing rules may not be beneficial to all consumers, rendering them infeasible.

The remainder of this paper is structured as follows: Section 2 presents the RECom model; Section 3 discusses the determinant of the community's value; Section 4 discusses how the value can be shared within the RECom; Section 5 presents the numerical simulations and Section 6 concludes. In the Appendix, we provide additional information on self-consumption, sharing rules, and nomenclature.

2. The RECom model

2.1. Description of the community

We model a renewable energy community (RECom) composed of a set M of m households located in a particular neighborhood. There are two types of members: "prosumers" (P), who have decentralized production units (DPU), typically solar panels on their rooftops, and traditional "consumers" (C). There is a subset M^P of M with m^p prosumers and a subset M^c of M with m^c traditional consumers, with $m^p + m^c = m$. We use the index i to refer to an arbitrary member.

The RECom organizes power exchanges between the members and the energy system. The RECom buys the production surplus of the prosumers and invests in a battery to store electricity.[1] The community then sells its power either to the members or to the retailers. All the power exchanges take place on the public grid and each household and the battery are equipped with meters to measure the power exchanges (injection and withdrawal). Power exchanges are measured at every time step t (for instance, every $\frac{1}{4}h$).

The community does not meet all the electricity needs of its members, and they have, in addition to the community contract, a contract with an energy retailer to purchase the additional power they require. The structure of the RECom and the power exchanges are illustrated in Fig. 1.

2.2. Community production and consumption

Community members have given consumption and production profiles. For each consumer $i \in M^c$, the consumption recorded by the meter at every time step t is denoted by $Q_i(t)$. Prosumers are equipped with dual meters recording, at every time step, their exchanges with the grid: power injections when they have a production surplus and

[1] RECom could also invest in production assets. To better fit our numerical simulations, we consider that the only asset owned by the community is a battery.

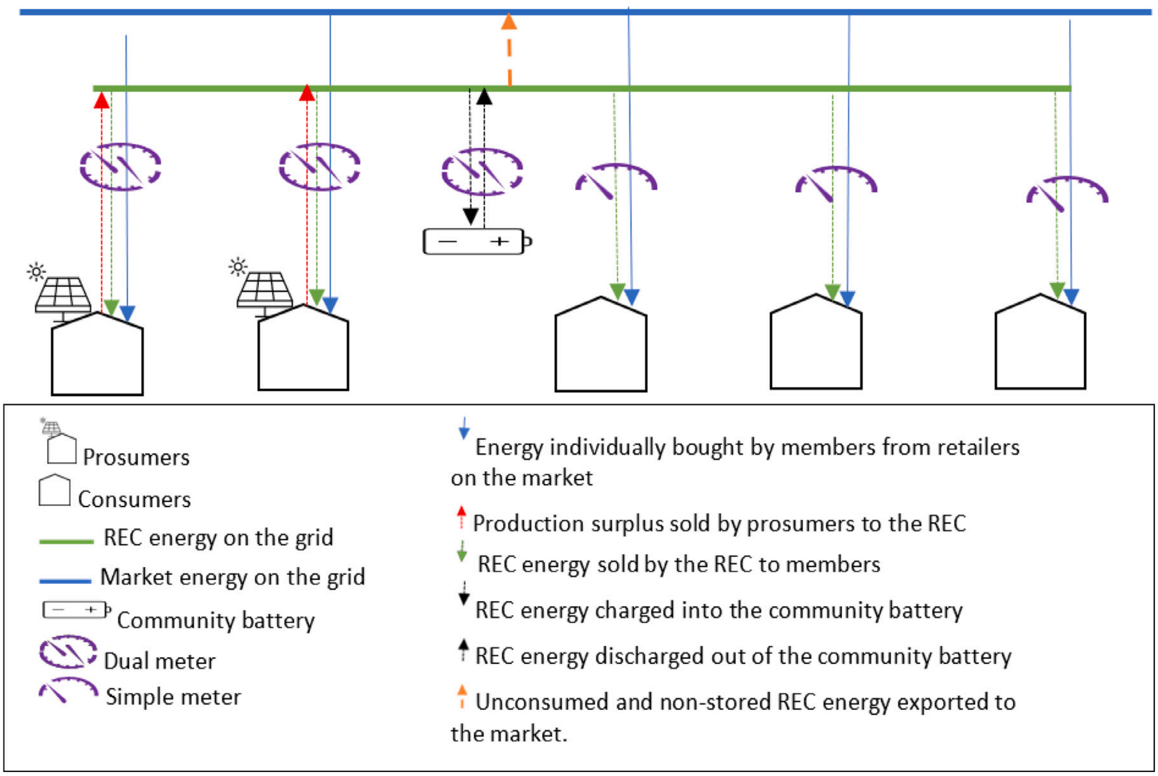

Fig. 1. REcom organizational structure.

withdrawals when their production is insufficient to cover their consumption. For each prosumer $i \in M^p$, the meters record, at every time step t, the consumption $Q_i(t)$ and the production surplus $K_i(t)$. By construction, if at time t $Q_i(t) > 0$ then $K_i(t) = 0$ and vice versa.

At each time step t, community consumption is defined as $Q(t) = \sum_{i \in M} Q_i(t)$ and community production as $K(t)$ is the sum of the prosumers' production $K^p(t) = \sum_{i \in M^p} K_i(t)$.

We consider a time horizon of T periods and the aggregate consumption and production over these periods are denoted by Q and K, with $Q = \sum_{t=1}^{T} Q(t)$ and $K = \sum_{t=1}^{T} K(t)$.

The electricity produced by the community will be either consumed by the members directly or after being stored in a battery, or sold to the grid. The electricity produced by the community and consumed by its members is referred to as *collective self-consumption*. We denote the collective self-consumption at time t by $H(t)$, and $H = \sum_{t=1}^{T} H(t)$. The electricity that is not self-consumed is exported to the grid, and we denote the exports by $X(t)$ and $X = \sum_{t=1}^{T} X(t)$. In Appendix A, we explain how self-consumption can be computed from the meter readings. The meter of the battery is essential to compute the level of self-consumption. If the battery is empty at the end of the T period, we have by definition $K = H + X$.

2.3. Self-consumption, self-production and self-sufficiency

Given Q, K, and H, we define the following ratios:

- **The self-consumption ratio** (ϕ) is the percentage of community production that is collectively self-consumed: $\phi = \frac{H}{K}$. A higher value of ϕ indicates that the community consumes a larger fraction of its production and, by doing so, the community creates more value.
- **The self-production ratio** (ψ) is the percentage of community consumption that is covered by community production: $\psi = \frac{K}{Q}$. The ratio ψ measures the relative importance of community production to its consumption.
- **The self-sufficiency ratio** (ω) is the percentage of consumption covered by the collective self-consumption: $\omega = \frac{H}{Q}$. It measures the relative importance of satisfying the electricity needs of community members.

2.4. The REcom and the energy market

We denote by p^m the retail price of electricity. This price includes the commodity cost, the grid fees and all the taxes and surcharges applied by the regulator and the state. Consumers in the community buy $Q - H$ from the market at this price p^m. We denote by p^x, the price at which energy retailers buy electricity from the community. The price p^x is the price effectively perceived by the community i.e., net of any injection fee paid to the grid. Individual prosumers, if they are not part of a community, can sell their surplus to the grid at this price. In our model, all prices are time-invariant[2] and we suppose that $p^m > p^x$.

Collective self-consumption takes place on the public grid. The regulator can impose a volumetric grid fee on the collective self-consumption, and we denote this fee by δ. In some jurisdictions, the regulator applies a reduction of the grid fee for collective self-consumption.[3]

2.5. Community costs

The community incurs two different types of costs. On the one hand, a community should be established as a legal entity, which

[2] With time-varying prices, the community can arbitrage between selling electricity to the members or to the market. This creates potentially more value for the community but complexifies the management of the battery.

[3] Several European countries offer discounts on grid fees for energy communities to encourage local renewable energy production and consumption. A good illustrative example is the region of Brussels that offer a 100% discount for the electricity exchanges within the same building, a 50% discount for exchanges below the same low voltage feeder and no discount for all the other exchanges.

incurs administrative costs. These costs include providing information to members, the contracting process, sharing energy, and preparing bills, among others. On the other hand, the community invests in its own assets implying investment and maintenance costs. We denote the operational costs by C^o and the asset cost by $\bar{C}$. The operational cost is linked to the volume of exchange within the community, and the asset cost is related to the asset size, which we will assume to be fixed.

2.6. The community contract

The RECom proposes a contract to households interested in joining the community. The community contract is a 4-tuple that specifies (1) the price (p^p) at which electricity is bought from prosumers; (2) the price (p^s) at which electricity is sold to members; (3) the membership fee (F) that prospective members should pay to join the community and (4) a sharing rule (α) specifying how electricity is shared among members. The sharing rule specifies the fraction α_i of the collective self-consumption that is allocated to member i, with $\sum_{i\in M}\alpha_i = 1$. We denote the community contract by $\Gamma = \{p^p, p^s, F, \alpha\}$.

3. Creating value

3.1. Profit

The profit of the community is defined as

$$\pi = (p^s - \delta)H + p^x X - p^p K^p - C^o - \bar{C} + mF. \tag{1}$$

The first two terms are the revenue from selling the production K to the members and the grid. The next three terms represent the costs of buying electricity from prosumers, investing in storage, and administrative costs. The last term is the total membership fee paid by the members.

3.2. Benefits to members

The individual benefit (denoted B_i) of participating in the community is given by the following equations, the first for the prosumers, and the second for the consumers:

$$B_i = (p^m - p^s)\alpha_i H + (p^p - p^x)K_i - F \qquad \text{for } i \in M^p, \tag{2}$$

$$B_i = (p^m - p^s)\alpha_i H - F \qquad \text{for } i \in M^c. \tag{3}$$

Consumers and prosumers benefit when they purchase electricity sold by the community at a price p^s that is lower than the market price p^m. Prosumers have an additional benefit as they sell their production surplus at a premium price p^p to the community rather than selling it into the market at a lower price p^x.

The total benefit for the members is:

$$B = \sum_{i\in M} B_i = \underbrace{(p^m - p^s)H - mF}_{\text{for the } m \text{ members (prosumers and consumers)}} + \underbrace{(p^p - p^x)K}_{\text{For the } m^p \text{ prosumers}} \tag{4}$$

3.3. Value

The community should operate on a non-negative profit basis and guarantee a non-negative benefit for each member, meaning that the community contract should satisfy conditions $\pi \geq 0$ and $B_i \geq 0$. A necessary condition to satisfy these constraints is to create some positive value V equal to the sum of the members' benefit and the profit: $V = B + \pi$ and V must be non-negative, which is equivalent to:

$$V = B + \pi \geq 0 \Leftrightarrow (p^m - \delta - p^x)H - \bar{C} - C^o \geq 0. \tag{5}$$

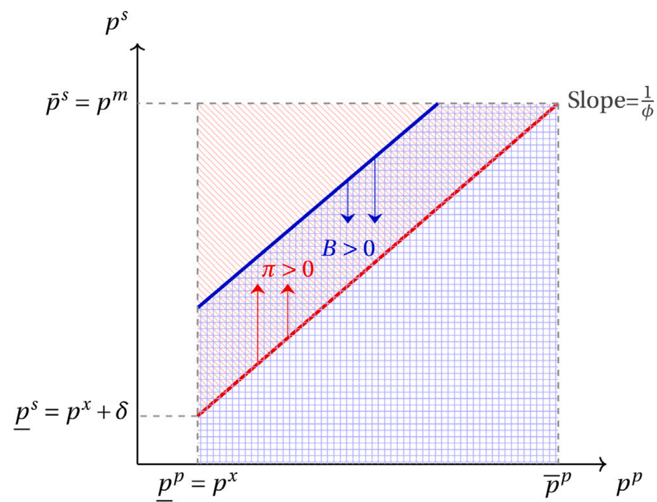

Fig. 2. Set of possible prices p^s and p^p.

This equation defines the total value created by the RECom, and this value (if positive) will be shared among the members and the shareholders. Notice that this value is independent of the community contract Γ. Internal prices and the sharing rule have no impact on the value created. They are merely instruments for redistributing value among members and shareholders (Gautier et al., 2025).

3.4. Feasible communities

To conduct our analysis, we will assume that the membership fees cover the cost of storage and operational expenses. To simplify the notation, we suppose that $\bar{C}$ denotes the sum of these two costs. The fee is the same for all members, irrespective of their type: $F = \frac{\bar{C}}{m}$. We have:

$$\pi = (p^s - \delta - p^x)H - (p^p - p^x)K, \tag{6}$$

$$B = (p^m - p^s)H + (p^p - p^x)K - \bar{C}, \tag{7}$$

$$V = (p^m - \delta - p^x)H - \bar{C}. \tag{8}$$

From Eq. (6), we can derive the zero-profit constraint which is a locus of prices (p^s, p^p) along which the profit is equal to zero. This locus is given by the following equation and represented by the red line in Fig. 2:

$$p^s = p^x + \delta + (p^p - p^x)\frac{1}{\phi}. \tag{9}$$

The locus is increasing with a slope equal to $\frac{1}{\phi} > 1$. If the community pays more to buy electricity from prosumers, it should sell the self-consumed electricity at a higher price. As the buying price p^p cannot be below p^x and the selling price p^s cannot be above p^m, we can identify the two extreme points of the locus as $(\underline{p}^p, \underline{p}^s) = (p^x, p^x + \delta)$ and $(\overline{p}^p, \overline{p}^s) = (p^x(1-\phi) + \phi(p^m - \delta), p^m)$. All price combinations within the red triangle of Fig. 2 ensure a profit for the community.

Similarly, from Eq. (7), we can define a locus of prices guaranteeing a zero benefit to the members:

$$p^s = p^m - \frac{\bar{C}}{H} + (p^p - p^x)\frac{1}{\phi}. \tag{10}$$

The locus is represented by the blue line in Fig. 2. All the price combinations below the blue line, represented by the blue area, give a positive total benefit to the members.

The zero-profit line and the zero-benefit line have the same slope and the zero-benefit locus is above the zero-profit locus if $p^m - \frac{\bar{C}}{H} \geq p^x + \delta$, that is, if $V \geq 0$. The set of feasible communities is the intersection between the blue and the red areas. As we mentioned above, this set is non-empty under the condition $V \geq 0$.

4. Sharing value

Eq. (8) defines the value created by the community and, thus, the value that must be shared among the participants. For that, the community has multiple instruments, including a sharing rule to allocate self-consumption among members and a system of internal prices.

4.1. Sharing value: equality v. efficiency

The energy-sharing rule and internal pricing jointly dictate how the RECom value is divided among members. We investigate how this distribution of value could be done according to two potential scenarios explored in the literature: equal distribution and distribution based on individual endowments or characteristics of members.

To assess the value distribution within the RECom, we adopt the framework developed by Ouvrard et al. (2022) in the context of common-pool resource sharing. Through an experimental approach, the authors investigated the factors influencing the selection of a sharing rule for water distribution among farmers. The latter is equipped with technology that correlates resource consumption (water) with individual monetary gains. Participants choose among two rules: an *egalitarian* rule that evenly divides the available resources without considering the technology and a *loss-avoidance* or *efficiency* rule that prioritizes users with the more profitable yet riskier technology. A survey was conducted to assess individuals' adherence to fairness principles. The results revealed that participants often vote for sharing rules that align with their personal self-interest. However, when subjects express their fairness principles before voting, there is a tendency towards greater egalitarianism. Interestingly, the adherence to fairness principles does not directly impact subjects' votes but instead exerts an indirect influence through their choice of technology.

This study considers two types of allocation: a *fair* scheme that divides the RECom value among participants in an egalitarian manner and a *type-based* scheme where value is divided according to consumption. In both cases, the allocation is constrained.

To quantify the degree of fairness of an allocation and to compare them, we use the Gini index. A perfectly fair value sharing scheme would result in each participant receiving an identical benefit, represented by the equation $B_i = \frac{V}{m} \forall i \in M$, yielding a Gini index of 0. We will check when this egalitarian allocation is feasible.

4.2. Sharing rules

The self-consumed electricity is sold to members at a discounted price p^s. As this cheap electricity is scarce, finding a rule to allocate H among the community members is necessary.

As mentioned above, many ways to share energy (Mustika et al., 2022; Abada et al., 2020a; Roy et al., 2023; Fina et al., 2022; Moncecchi et al., 2020) can be considered by the community. A priori, the community can allocate the energy as it wants. There are however two technical constraints. A priori, the community can allocate the energy as it prefers, subject to two technical constraints. First, the volume of self-consumed electricity is defined above by the consumption and production profile (see Appendix A). Second, a member cannot be allocated more self-consumption than its consumption over the period.

Electricity flows according to Kirchhoff's laws, and the allocation of self-consumed electricity among members is done ex post for billing purposes. In this perspective, the community decides on a sharing rule to allocate the collective self-consumption H to members. We propose two simple sharing rules, per-capita and pro-rata consumption. In both cases, the repartition of power can be done either at every time step t or for a longer period, for instance every hour, day, month, or year. The choice of a time interval is important as over a period τ a member cannot be allocated more electricity than its actual consumption: $\alpha_i H(\tau) \leq Q_i(\tau)$. With the per-capita key, this constraint is more likely to be binding for shorter periods, leading to a less equal distribution of electricity. By construction, this constraint is always satisfied with the pro-rata key.

The per-capita repartition key is a sharing rule allocating the same quantity of electricity to all members:

$$\alpha_i = \frac{1}{m}. \tag{11}$$

If $\alpha_i H(\tau) > Q_i(\tau)$, any excess $\alpha_i H(\tau) - Q_i(\tau)$ is shared among the $m-1$ remaining members. In the Appendix (Appendix B), we provide a detailed algorithm that outlines how this excess electricity is allocated among members using an iterative per-capita repartition key.

The pro-rata repartition key is a sharing rule that allocates to each member a quantity of electricity corresponding to its share of consumption:

$$\alpha_i = \frac{Q_i(\tau)}{Q(\tau)}. \tag{12}$$

The community can combine these two simple sharing rules and allocate part of the self-consumption on a pro-rata basis and the remaining part on a per-capita basis:

$$\alpha_i = \beta \frac{Q_i(\tau)}{Q(\tau)} + (1-\beta)\frac{1}{m}. \tag{13}$$

4.3. Individual participation constraints

A positive aggregate benefit (see Fig. 2) does not imply that all consumers participate in the community; thus, we need to incorporate individual participation constraints. In other words, $B \geq 0$ does not guarantee that $B_i \geq 0$ for all $i \in M$. We examine these constraints relative to the two main sharing rules: per-capita and pro-rata consumption. With the explicit sharing rule, we can identify the subset of prices that are feasible and calibrate these prices in the numerical model.

4.3.1. Per-capita sharing rule

Consider first the per-capita sharing rule. In this case, the benefit of a consumer $i \in M^c$ is equal to[4] $B_i = (p^m - p^s)\frac{H}{m} - \frac{\bar{C}}{m}$ and B_i is positive if:

$$p^s \leq p^m - \frac{\bar{C}}{H}. \tag{14}$$

This constraint puts further restrictions on the set of feasible contracts, but the set of feasible contracts remains non-empty.

Note that, even with a per-capita sharing rule, some consumers may receive less than others because they have a low consumption i.e., for some periods, their consumption is such that $Q_i(\tau) \leq \frac{H(\tau)}{m}$. This situation, in turn, reduces their benefit and strengthens the above participation constraint.[5]

4.3.2. Pro-rata sharing rule

With the pro-rata sharing rule, the consumers with a low α_i have a low benefit. Furthermore, for those with $\alpha_i \leq \frac{1}{m}$, the benefit is lower than with the per-capita sharing rule. Therefore, individual participation constraints are more complicated to satisfy. In particular, the participation constraint should be satisfied for the consumer i with the lowest α_i. Define $\underline{\alpha} = Min_{i \in M^c} \alpha_i$, the participation constraint is:

$$p^s \leq p^m - \frac{\bar{C}}{H}\frac{\underline{\alpha}}{m}. \tag{15}$$

This constraint is stronger than in the per-capita sharing rule, and it may not be satisfied if $\underline{\alpha}$ is too low. In such cases, the perimeter and composition of the community should be adapted.

4 Prosumers have, in principle, a higher benefit because their receive a compensation $p^p \geq p^x$ for the electricity they sell.

5 If prosumers are in such a situation, their participation constraints can be satisfied by increasing the buying price p^p.

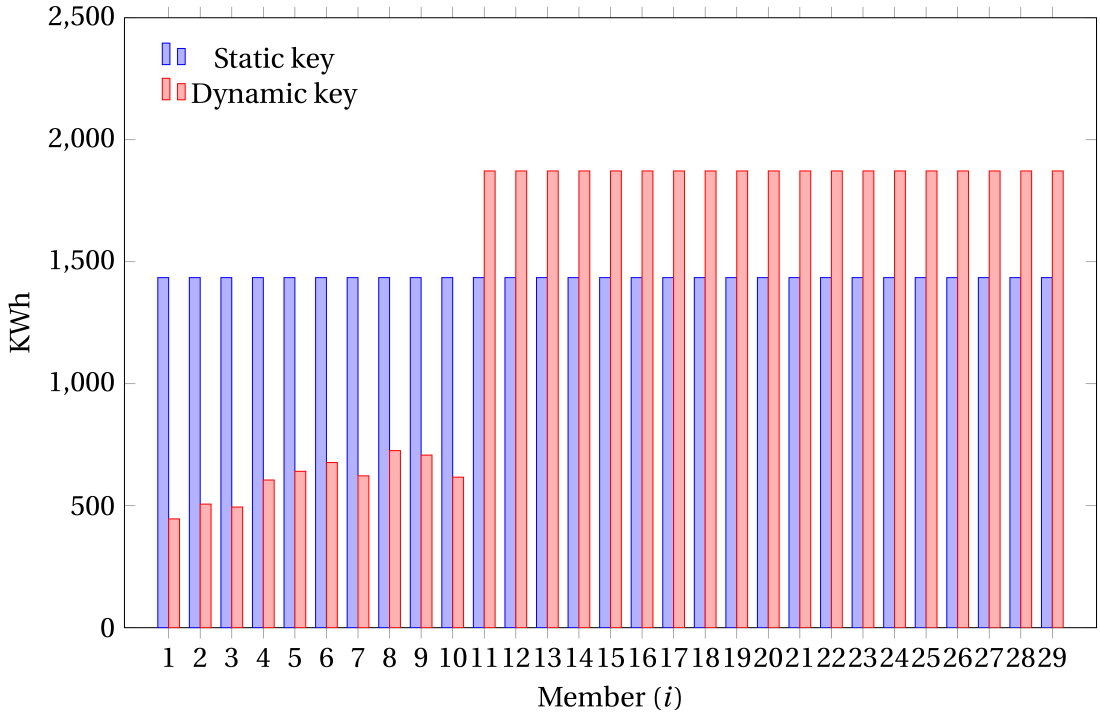

Fig. 3. Self-consumption for per-capita key: static vs dynamic.

4.4. The choice of a community contract

The choice of a community contract should reflect the community's preferences. In this article, we consider two possible objectives for the community: an equal sharing of the benefits and a benefit proportional to individual consumption and production. The first objective is associated with the per-capita sharing rule, and the second with the pro-rata sharing rule. But, the community should choose a price within the admissible set that we defined above, which is consistent with its objective. In other words, the choice of sharing rules and the choice of prices should be aligned to reach the community's goal.

In particular, if the community wants to achieve an equal distribution of the benefits, it is recommended to set $p^p = p^x$ and to select the lowest possible price p^s. In this case, all members, whether prosumers or consumers, would have the same benefit. Increasing p^p above p^x would only be used if prosumers do not receive the same share of self-consumption as consumers, i.e., p^p could be used to increase the benefits of prosumers, but it should be used only if necessary.

Likewise, if p^s is close to p^m, the benefit of self-consumption is limited[6] and there is a slight advantage of using a pro-rata sharing rule. If the community uses a pro-rata sharing rule, the benefit of self-consumption should be large enough.

5. Numerical simulation

5.1. Data

5.1.1. RECom organization and electricity flows

We utilize data from a virtual energy community situated in a suburban neighborhood in Belgium. The data come from simulations conducted by ENGIE Laborelec. The community comprises 29 members, among whom 19 are traditional consumer members, and 10 are prosumers, who own individual solar panels with a total capacity of 52 kWp. Nine members own electric vehicles (EVs). The community does not produce electricity; instead, it uses a battery with a 75 kW power rating and a 150 kWh capacity.[7] EVs are considered individual storage systems, whereas the battery serves as a collective storage system for all members. There are 30 m, 29 for members, and one for the RECom battery. The meters of the prosumers record the consumption ($Q_i(t)$) and the injection ($K_i(t)$). The meter of the battery records charging and discharging but the community does not pay the grid fee δ for power exchanges with the battery to avoid double counting.

Table 1
Members' annual electricity flows in MWh.

Variable	SD	Mean	Min	Med	Max
$K_i \mid i \in M^p$	1.01	4.21	2.55	4.08	5.59
$Q_i \mid i \in M^p$	1.27	4.45	1.54	5.20	5.46
$Q_i \mid i \in M^c$	1.32	4.31	1.93	4.23	6.34

The dataset encompasses one year of simulated electricity flows of households forming the RECom. It includes data on electricity consumption, production export, and storage, all recorded in kilowatt-hours (kWh) through smart meters for each member (i) in 15 min intervals over the year (35,040 time steps). Members' indexes are determined by their type and by their annual consumption such that $i = 1, 2, \dots, 10 \in M^p \mid Q_1 \le Q_2 \le \dots \le Q_{10}$ and $i = 11, 12, \dots, 29 \in M^c \mid Q_{11} \le Q_{12} \le \dots \le Q_{29}$. Members' annual electricity flows are summarized in MWh in Table 1.

5.1.2. Market prices and costs

The following table presents the market price used in this study, along with the asset and operating costs. For the battery, we compute the levelized cost of storage (LCOS).[8] The operational cost is equal to €0.05 per kWh self-consumed and included in the cost $\bar{C}$ (see Table 2).

[6] In this case, the community realizes a high revenue from self-consumption and it can be redistributed to shareholders (π), to prosumers (by increasing p^p) or to all the members by reducing the membership fee F.

[7] This means that charging at full power, from zero, the battery can store 150 kWh in two hours.

Table 2
Market prices and costs.

Price	Value	Remark
p^m	€0.281/KWh	Retail price proposed by a Belgian supplier (ENGIE, 2023)
p^x	€0.072 /KWh	Buying price proposed by a Belgian supplier (ENGIE, 2023)
δ^s	€0.08 /KWh	Average grid tariff (Wallonia), 2023 (CWAPE, 2023)
C^o	€0.05 /KWh	Price applied in a typical RECom
$\bar{C}$	€3079	Maintenance and asset cost

Table 3
RECom KPIs and value.

Description	Value
Self-consumption ratio ϕ	0.99
Self-production ratio ψ	0.33
Self-sufficiency ratio ω	0.34
RECom value V	€2287.5
Membership fee $F = \frac{\bar{C}}{m}$	€106.20

5.1.3. Key performance indicators and the community value

The total consumption of all members over a year (Q) is 126.41 MWh; the total production of prosumers available for the community (K) is 42.11 MWh. Thanks to the battery, almost all the production is self-consumed with only 1.19% being injected into the grid. The high self-consumption ratio of 98.81% derives from the use of the community battery which stored more than 16.71 MWh over the year. Without storage, only 59.12% of the production would have been collectively self-consumed. Some key performance indicators are presented in Table 3.

5.2. Sharing electricity

Hereafter, we provide the sharing of electricity with the per-capita and the pro-rata repartition keys. For each key, we conduct two simulations, the first (dynamic), where the repartition is implemented every 15 min, and the second (static), where the repartition is implemented annually. The repartition of electricity among members is presented in Figs. 3 and 4.

The sharing rules offer different individual self-consumption options to each member, thereby affecting the extent to which each member's electricity needs are covered by RECom electricity. With both rules, the individual self-consumptions exhibit a higher degree of variability when sharing occurs at every time step compared to sharing on an annual basis.

On an annual basis, the per-capita rule distributes 1434.84 kWh to all members. In contrast, on a $\frac{1}{4}$ hour basis, it allocates different electricity amounts to prosumers, ranging from 445.87 kWh to 725.76 kWh, and assigns a fixed 1872 kWh to each consumer; thus, consumers receive more, while prosumers receive less. This difference comes from the fact that during solar production periods, some prosumers have a power surplus, and therefore, they are not eligible for self-consumption.

With the pro-rata sharing rule, by construction, small consumers and prosumers receive less, and larger consumers and prosumers receive more. With the static keys, 9 out of 19 consumers and 6 out of 10 prosumers have a higher self-consumption with the pro-rata allocation. With the dynamic keys, eight consumers but no prosumers have a higher self-consumption.

Finally, with both the per-capita and pro-rata rules, consumers have more benefits when the key is dynamic, and prosumers have fewer. But, allocating power is only one part of the story, and the community uses internal prices to convert kWh into income.

5.3. Admissible prices

The total value generated by the community amounts to €1357.[9] If we suppose that the community operates as a non-profit ($\pi = 0$), the community redistributes all this value to the members, in the form of a higher price paid to prosumers ($p^p \geq p^x$) or a lower price paid for self-consumption ($p^s \leq p^m$).

Under $\pi = 0$, all possible price sets are located on the red line in Fig. 2. This line is defined from $(p^S, p^p) = (0.072, 0.152)$ to $(\overline{p}^S, \overline{p}^p) = (0.199, 0.281)$ and has a slope of $1.\overline{012}$. However, all these prices cannot be implemented as they also need to satisfy the participation constraints.

With the per-capita static key, all members have the same self-consumption volume ($H_I = \frac{H}{M} = 1434$ kWh). Therefore, the community can implement a perfectly egalitarian sharing of the value by selecting a price p^p equal to the market price p^x and the lowest possible price for selling electricity; that is the community selects $(p^p, p^s) = (\underline{p}^p, \underline{p}^s) = (0.072, 0.14)$. With these prices, each member receives a benefit of Û78.8. The community can increase prices, but the benefit to prosumers will increase as they receive an additional profit from selling their surplus, while the benefit to consumers decreases as they buy electricity from the community at a higher price. The maximum price that the community can implement is $(p^p, p^s) = (0.126, 0.206)$ corresponding to the participation constraint of the consumers. The community can implement all prices on the zero-profit locus between these two extreme points.

With the per-capita dynamic key, prosumers have lower self-consumption, and if the community applies the lowest prices $(\underline{p}^p, \underline{p}^s)$, their benefit is too low to cover the entry fee. To satisfy their participation constraint, they must receive a price p^p above the market price p^x. We can use the participation constraints of the prosumers and the consumers to identify the set of feasible prices on the zero-profit locus. With the per-capita dynamic key, the lowest prices are $(p^p, p^s) = (0.095, 0.190)$, and the highest prices are $(p^p, p^s) = (0.143, 0.224)$. The choice of a given price on the locus has redistributive consequences that we discuss in the following subsection.

[8] As viewed by several studies (IEA, 2020; Branker et al., 2011; Ordóñez Mendieta and Hernández, 2021; Allouhi et al., 2019; Belderbos et al., 2017), levelized costs can be used to value the unit cost of energy. In this model, the battery cost charged by self-consumed KWh corresponds LCOS given by

$$LCOS = \frac{\sum_y (CAPEX_y^s + OPEX_y^s) \times (1+r)^{-y}}{\sum_y STORE_y^s \times (1+r)^{-y}}$$

With

$CAPEX_y^s$	Capital expenditures of storage for the year y
$OPEX_y^s$	Operational expenditures of storage (maintenance, administration, etc.) for the year y
$(1-r)^{-y}$	The discount factor for year y, with r being the discount rate
$STORE_y^s$	Energy stored in year y

[9] We compute values over an annual time frame corresponding to data. However, it is also feasible to conduct a comprehensive, long-term analysis, taking into account factors such as the lifespan of assets and time-varying variables such as the discount rate, inflation rate, energy consumption patterns, and more.

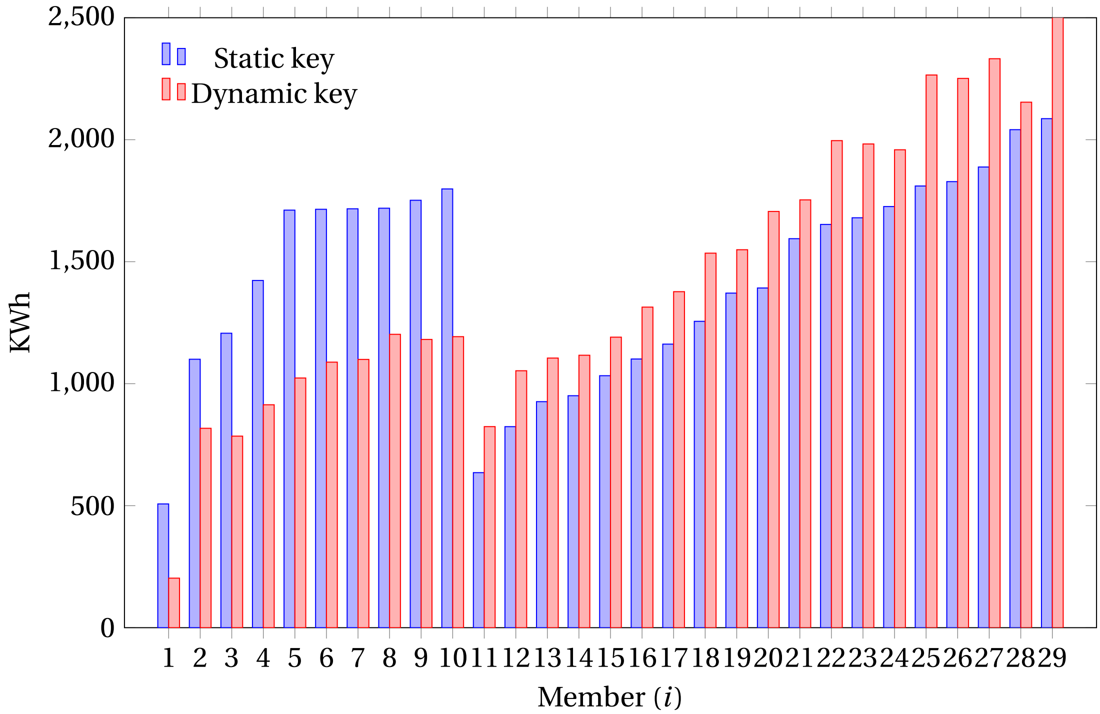

Fig. 4. Self-consumption for pro-rata key: static vs dynamic.

With the pro-rata key, be it static or dynamic, there is no price on the zero-profit locus that satisfies all the participation constraints. It is thus impossible to use a pro-rata key in the community. It is therefore impossible to use a pro-rata key in the community. To satisfy the participation constraint of the consumer with the lowest consumption ($i = 11$), the community should choose a low price p^s. With the static key, the price p^s should be below 0.118. This price is below the lowest admissible price $\underline{p}^s$. Hence, it is not possible to implement the pro-rata key in our example.

In our numerical simulation, we have different profiles for prosumers and consumers, but all members are residential, and the variability in their consumption and production is relatively limited (See Table 1). Despite this, it is not possible to implement a key proportional to consumption.

The community can reduce its size, but without a guarantee that excluding the smallest consumers would be enough to implement the pro-rata key. Contractual solutions can also be implemented. The RECom can use menu pricing and offer differentiated fees for members, for instance, the choice between a contract with a high fee and low p^s and a contract with a low fee and a high p^s. Larger consumers would prefer the first option, smaller one the second. Alternatively, the RECom can use a mixed sharing key (defined in Eq. (13)), making the redistribution of the self-consumed electricity more egalitarian.[10]

5.4. Inequality

Finally, we demonstrate that an egalitarian sharing rule does not necessarily result in an egalitarian distribution of benefits. Inequality can be created by prices.

To illustrate, we consider the scenario in which the community chooses the dynamic per-capita sharing rule, for which the set of admissible prices is located on the zero-profit locus between points $(p^p, p^s) = (0.095, 0.190)$ and $(p^p, p^s) = (0.143, 0.224)$. The lowest point is given by the participation constraint of prosumer $i = 8$ (who has a low production surplus) and the participation constraint of the consumers gives the highest point.

To illustrate the redistributive consequences of prices, we represent on Figs. 5, 6, and 7, the individual benefits of each member and their decomposition into the benefits from selling electricity (for prosumers), the benefits of self-consumption, and the total benefits net of the fixed fee. We construct the benefit for three points on the locus, the two boundaries identified above and an intermediate point $(p^p, p^s) = (0.111, 0.207)$.

From the figures, it is clear that the interests of prosumers and consumers are antagonistic; the former prefer high prices, while the latter prefer low prices. To further compare, we calculate the Gini index for the three different prices. We observe that the two lowest price sets yield a similar value for the Gini, whereas the highest prices result in an uneven distribution of benefits, with all the benefits captured by the prosumers (see Table 4).

Table 4
Gini coefficient.

Prices (p^p, p^s)	Gini
(0.095, 0.190)	0.25
(0.111, 0.207)	0.24
(0.143, 0.224)	0.72

6. Conclusion

Although Renewable Energy Communities (REComs) are widely promoted for their multiple benefits, they remain underappreciated by the public, mainly due to the absence of a perceived added value. This paper seeks to quantify the value that REComs contribute to the energy system. Two key conditions are essential to justify their implementation and potential for replication: the distinct status of RECom-generated

[10] In our set-up, the community owns few assets, only a battery. REComs could in addition have productive assets (solar PV or wind turbines) financed by the members. In such a case, if the contributions to investment or the redistribution of value are unequal, it may be even more complicated to find feasible prices.

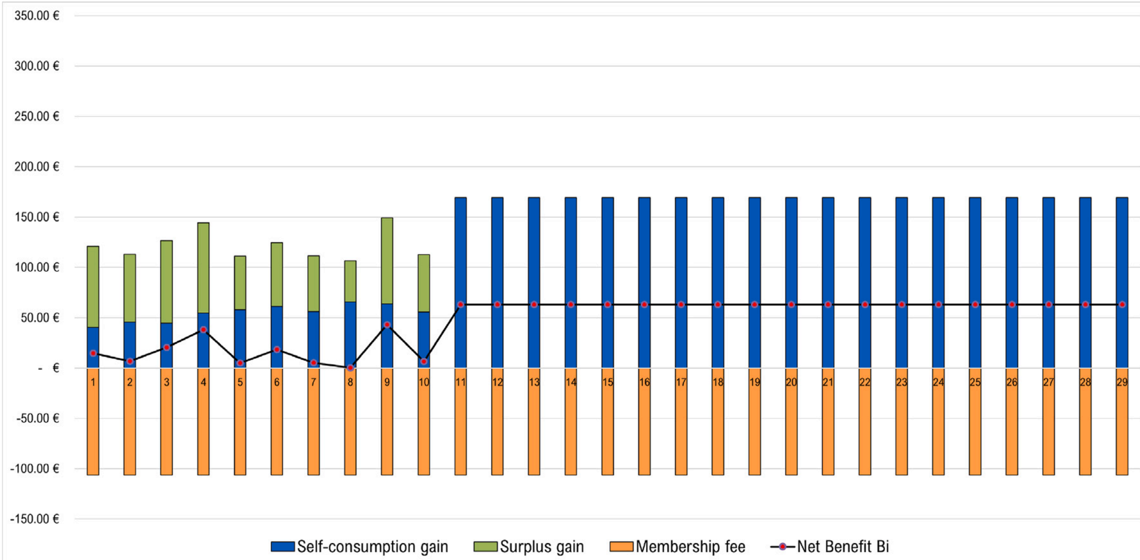

Fig. 5. Benefits with the prices $(p^p, p^s) = (0.095, 0.190)$.

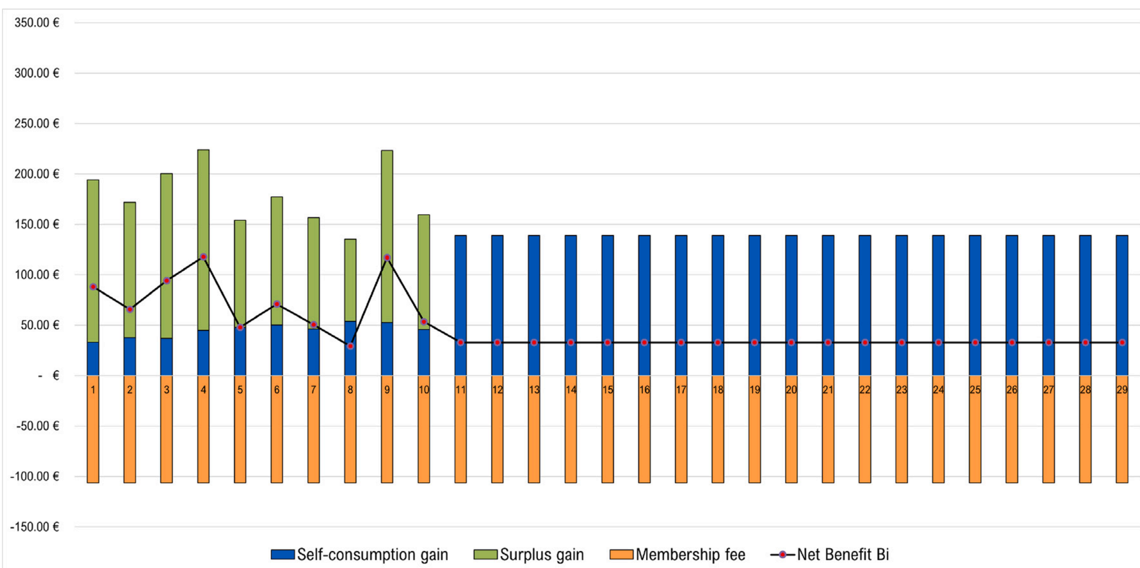

Fig. 6. Benefits with the prices $(p^p, p^s) = (0.111, 0.207)$.

electricity compared to market electricity and the tangible individual benefits for participating members.

The first condition highlights that renewable electricity produced and shared within a RECom enabled by Distributed Production Units (DPUs) is more affordable than electricity purchased from traditional retailers. The second addresses the citizen's central concern: "*What do I gain?*" To answer this, we use simple and commonly used allocation mechanisms for distributing the electricity produced within the community. Additionally, we propose a tariff structure designed to ensure a positive economic outcome for RECom participants.

The community comprises two types of members: prosumers, who both consume and generate energy using DPUs such as photovoltaic (PV) panels, and consumers, who do not produce energy but can still benefit from lower energy costs by joining the RECom. Each member has a unique consumption profile, making the redistribution of RECom value a complex task. To address this, the study introduces two key tools: energy-sharing rules and a tailored tariff scheme.

This analysis reveals the nuanced interplay between energy-sharing mechanisms and pricing strategies. While a specific sharing rule may benefit a member based on their profile and characteristics, the choice of pricing scheme can significantly influence the relative benefits among participants. Ultimately, individual outcomes depend on the community's overarching goals, whether they prioritize equity, aiming for a fair and balanced distribution of benefits, or efficiency, which tends to reward those who invest in production assets.

By providing a structured framework to evaluate and distribute value within REComs, this study contributes to making these communities more transparent, attractive, and scalable, paving the way for broader citizen engagement in the energy transition.

CRediT authorship contribution statement

Remy Balegamire: Writing – original draft, Visualization, Validation, Formal analysis, Data curation. **Axel Gautier:** Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

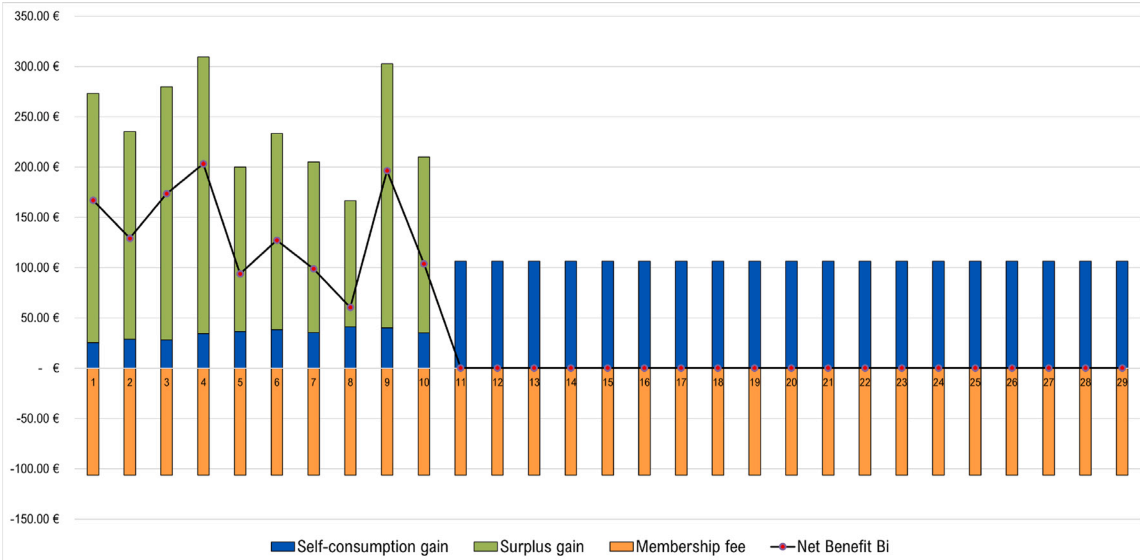

Fig. 7. Benefits with the prices $(p^p, p^s) = (0.143, 0.224)$.

Declaration of competing interest

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

Appendix A. Computing the collective self-consumption

The community battery has the capacity of $\bar{S}$ (maximum storable energy). Let us denote by $S(t)$, the battery status at date t and by $\Delta S(t) = S(t) - S(t-1)$, the evolution of the battery state between $t-1$ and t. The battery is charged if $\Delta S(t) \geq 0$ and discharged if $\Delta S(t) < 0$.

Given $Q(t)$ and $K(t)$, the following algorithm is designed to maximize the collective self-consumption over the total period. At each time t:

1. If $K(t) + S(t) \leq Q(t)$, $H(t) = K(t) + S(t)$, $X(t) = 0$ and $\Delta S(t) = -S(t-1) < 0$,
2. If $K(t) + S(t) > Q(t)$, $H(t) = Q(t)$, and
   - 2.1. If $Q(t) \geq K(t)$, $X(t) = 0$ and $\Delta S(t) = -(Q(t) - K(t)) < 0$,
   - 2.2. If $Q(t) < K(t)$,
     - 2.2.1. If $S(t) + (K(t) - Q(t)) < \bar{S}(t)$, $X(t) = 0$ and $\Delta S(t) = (K(t) - Q(t) > 0$,
     - 2.2.2. If $S(t) + (K(t) - Q(t) \geq \bar{S}(t)$, $X(t) = K(t) - Q(t) - (\bar{S}(t) - (K(t) - Q(t)) > 0$ and $\Delta S(t) = \bar{S}(t) - S(t) > 0$.

Appendix B. Per-capita repartition key

The repartition key works along the following algorithm:

0 Rank consumers according to their consumption : $Q_1 < Q_2 < \cdots < Q_N$.

1. round 1
   - If $nQ_1 \geq H$, then $H_i = \frac{H}{n} \forall i$ and stop.
   - If $nQ_1 < H$, then $H_1 = Q_1$ and move to next round.
2. Round 2
   - If $(n-1)Q_2 \geq H - Q_1$, then $H_i = \frac{H-Q_1}{n-1} \forall i > 1$ and stop.
   - If $(n-1)Q_2 < H - Q_1$, then $E_2 = Q_2$ and move to next round.
3. Round 3
   - If $(n-2)Q_3 \geq H - Q_1 - Q_2$, then $H_i = \frac{H-Q_1-Q_2}{n-2} \forall i > 2$ and stop.
   - If $(n-2)Q_3 < H - Q_1 - Q_2$, then $H_3 = Q_3$ and move to next round.

i Round i
   - If $(n-i+1)Q_i \geq H - \sum_{j<i} Q_i$, then $H_i = \frac{H-\sum_{j<i} Q_i}{n-i+1} \forall i > i$ and stop.
   - If $(n-i+1)Q_i < H - \sum_{j<i} Q_i$, then $H_i = Q_i$ and move to next round.
     With j, each member with a total consumption $Q_j < i \times Q_i$.

The allocation of energy can be summarized as follow:

1. If $\sum_{i=1}^{n} Q_i \leq H$, $H_i = Q_i \forall i$
2. If $\sum_{i=1}^{n} Q_i \geq H$, in this case, there exists a consumer i^* such that

$$(n - i^* + 1)Q_{i^*} > H - \sum_{j<i^*} Q_j,$$

$$(n - i^*)Q_{i^*-1} < E - \sum_{j<i^*-1} Q_j.$$

The allocation of energy is the following:

$$H_i = Q_i \forall i < i^* \text{ and } H_i = \frac{H - \sum_{j<i^*} Q_j}{n - i^* + 1} \forall i \geq i^*$$

.

Appendix C. Nomenclature of variables

In Table 5, we provide a nomenclature of variables used in our model.

Table 5
Nomenclature of variables.

Variable	Description
M	Set of member
M^p	Subset of prosumers
M^c	Subset of consumers
m, m^p, m^c	Number of members, prosumers, consumers
$Q_i(t)$	Consumption of member i at time t
$K_i(t)$	Production surplus of prosumer i at time t
$Q(t), K(t)$	Total consumption and production at time t
$H(t), X(t)$	Total collective self-consumption and export at time t
Q, K, H, X	Total consumption, production, collective self-consumption and export
T	Number of time periods (time horizon)
ϕ	Self-consumption ratio
ψ	Self-production ratio
ω	Self-sufficiency ratio
p^m, p^x	Retail and export prices
Γ	Community contract
p^p	Price paid by the REcom to prosumers
p^s	Price paid by the consumers to the REcom
F	Membership fee
α	Sharing rule for collective self-consumption
α_i	Share of member i
β	Parameter of the sharing rule
δ	Grid fee for collective self-consumption
C^o	Operational cost of the REcom
$\bar{C}$	Asset cost
π	Profit of the community
V	Total value created by the community
B, B_i	Total benefit for the members, for member i

Data availability

Data will be made available on request.

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