Pricing and sharing rules for energy communities

Remy Balegamire Baraka [*] Axel Gautier[†]

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Abstract

Prosumers and consumers can form together a renewable energy community (REC). Prosumers sell their production surplus to the community, which stores it or resells it to the members. To become a member, prosumers and consumers have to pay an entry fee to finance the community's assets, a battery in our example, and the management costs. Members can then buy electricity at a discounted price compared to the retail price and prosumers can sell their electricity at a premium price compared to the market price. The community should decide on those internal prices and on a sharing rule to allocate the collective self-consumption among members. In this paper, we analyze the role of prices and sharing rules to identify the communities that are feasible and the resulting allocation of the surplus among members. Depending on its objective, the REC can try to achieve an equitable allocation of the benefits among members or an efficient allocation. We use a numerical example to illustrate the resulting individual benefits for different prices and sharing rules.

Keywords: Energy communities, sharing rules, equity, efficiency

JEL Codes:

[*]HEC Liege, University of Liege, Belgium. E-mail: r.balegamire@uliege.be

[†]HEC Liege, University of Liege, Belgium. E-mail: agautier@uliege.be

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 of 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. This can be done both individually and collectively. Individual participation takes the form of investment in renewable energy technologies at the residences or at the workplace, by installing solar panels, adopting energy-efficient appliances, or modifying their consumption behavior (Gautier et al., 2019). Collective participation implies a collaboration among several individuals to pool resources, expertise, and aspiration for renewable energy initiatives (Rossetto et al., 2022). For instance, citizens may get together to finance and install wind farms, hydroelectric plants, or community solar installations to produce energy for their consumption.

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) and the magnitude of implementation of such participation differs across regions (Lelieveldt and Schram, 2023). It however has gained importance in the European Union's policy agenda with "Clean Energy for all Europeans" initiative and the Renewable Energy Directive ('RED II') adopted in 2018. The RED II brings forth the concept of Renewable energy communities (RECs) to facilitate the involvement of new stakeholders such as citizens, private companies, and public organizations.

A REC 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 REC can carry out various activities, such as energy generation and consumption, storage, sharing, flexibility, management, and trading (Rossetto et al., 2022). In this paper, 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).

A community can, within a local perimeter, share its production among its members, what is called *collective self-consumption*. Gautier et al. (2023) investigated the dynamics of interaction between RECs and the energy system and their potential to reduce the overall cost for the energy system. The authors show that RECs are profitable for participants and welfare-improving if a minimum amount of the energy produced within the REC is self-consumed inside the community. Renewable energy communities create value by self-consuming in the neighborhood what they produce. An appropriate regulatory framework for enabling collective self-consumption is needed, for example by offering discounted grid fees for collective self-consumption.

But creating value is only one side of the coin. Participants may have different motivation to join a community: environmental concern, community identity, social norms, etc. (Kalkbrenner and Roosen, 2016, Soeiro and Ferreira Dias, 2020, Süsser et al., 2022, Magnusson and Palm, 2019) but economic benefits is 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 like social inclusion, preference for redistributional justice (Hanke and Lowitzsch (2020)), return on investment, maximized self-consumption, etc. and the necessity to have a stable and mutually beneficial allocation among members.

In the literature, several authors have proposed mechanisms to share value within the community. Mustika et al. (2022) propose several keys that allocate the collective self-consumed energy among members. Those keys include static schemes, prorate-based approaches, cooperative game theory methods, and optimization-based strategies. The static key allocates the energy equally among members, while the pro-rated keys distribute the energy based on consumption, production, or investment levels. The hybrid and cascade keys combine static and prorate-based allocations, aiming for a more even distribution. The Shapley value method computes the marginal contributions of each member, while the minimization of collective bill and equal bill saving ratios are optimization-based approaches. Lastly, the maximization of the minimum individual savings balances collective and individual bill reduction goals. 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 REC manager will allocate energy to the 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 than the return on investments are considered. Fina et al. (2022) show that the dynamic allocation which allocates energy such that optimal usage of production assets is guaranteed results in 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) show that communities often fail to redistribute benefits to the most vulnerable groups of participants which are then underrepresented in the communities. Other authors (Abada et al., 2020a,b, Moncecchi et al., 2020) examine game theory-based methods to allocate energy or energy-related benefits to REC members. They recommend to use sophisticated mechanisms, like Shapley value, to share the benefits among members, as simple sharing rules may lead to unstable community configurations.

By contrast, regulators and REC managers often propose simple sharing rules, like per-capita or pro-rata consumption to allocate energy among members because they are easily understood by members and their implementation is not too 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 an allocation related to usage.

In this paper, we consider the question of sharing value within a community, composed of prosumers and consumers. Prosumers sell their production surplus to the community who store it or resell it to the members. To become a member, prosumers and consumers have to pay an entry fee to finance the community's assets, a battery in our example, and the management costs. Members can then buy electricity at a discounted price compared to the retail price and prosumers can sell their electricity at a premium price compared to the market price.

The community creates value by collectively self-consuming the energy surplus bought to the prosumers and the community invests in a battery to maximize the collective self-consumption. To share the value it creates, the community has two instruments: the internal prices for energy and the sharing rule. The sharing rule allocates the collectively consumed energy to each member, the prices transform energy flows into value.

We first identify the prices and sharing rules that are feasible within a community. A feasible community should create enough value collectively and distribute the value in order to guarantee that each member has a benefit if he or she joins the community. Next, we compare different prices and sharing rules and look at the resulting repartition of value. For that, we use the data from a virtual energy community in Belgium. Taking all constraints into account, we show how the instruments can be used to favor either an egalitarian sharing of the value or an sharing of the value which is more linked to the members' individual profile, in our case their consumption profile. The choice of a repartition depends on the members' and the community's preferences and objective.

The remainder of this paper is structured as follows: Section 2 presents the REC model, Section 3 discusses how value can be shared within the REC, Section 4 presents the numerical simulations and Section 5 concludes.

2 The REC model

2.1 Description of the Community

We model a renewable energy community (REC) composed of a set M of m households located in a particular neighborhood. There are two types of members "prosumers" (P), who have a decentralized production units (DPU), typically solar panels on their rooftop, 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 REC organizes power exchanges between the members and with the grid. The REC buys the production surplus of the prosumers and, in addition, it invests in assets to produce and store electricity. The community then sell its power either to the members or to the grid. All the power exchanges take place on the public grid and each household is 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 cover all the energy needs of its members and they have, in addition to the community contract, a contract with an energy retailer to buy the additional power they need. The structure of the REC is illustrated in Figure 1.

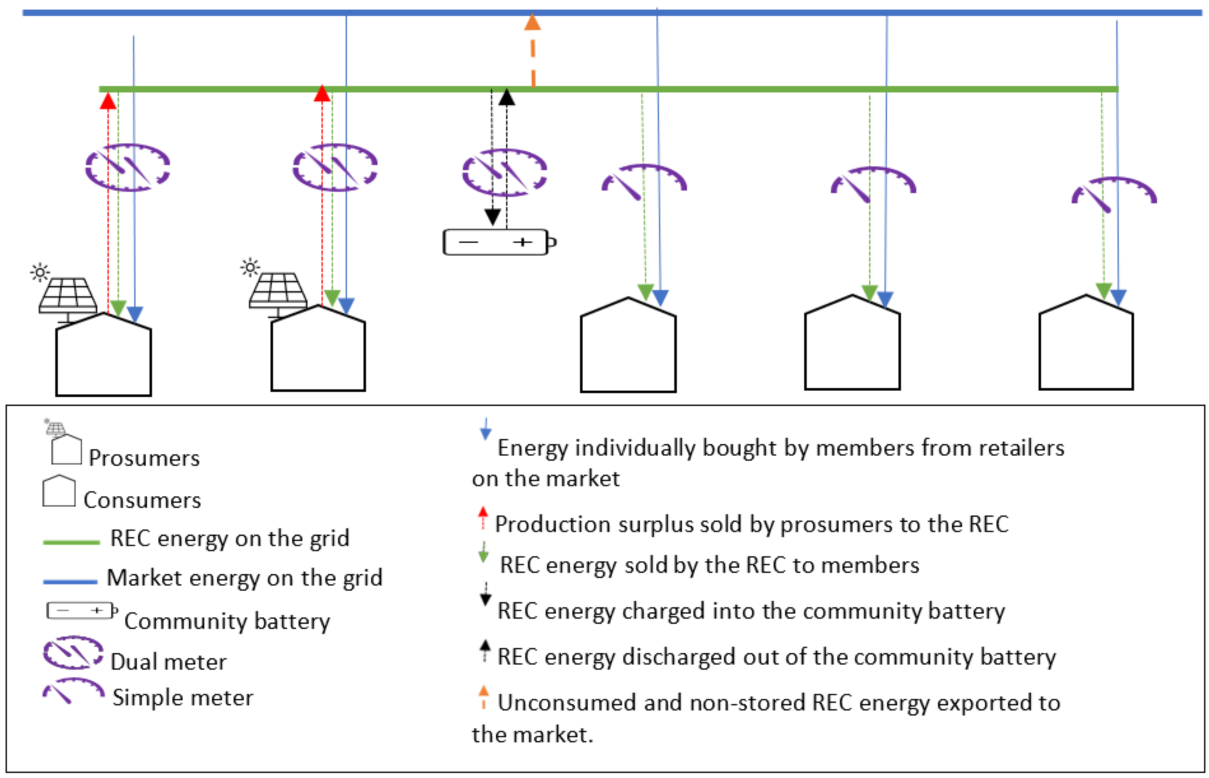

Figure 1: REC organizational structure

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 consumption if their production is insufficient to cover their need or their energy surplus injected to the grid and sold to the community if their production exceeds 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 $K_i(t)$. By construction, if at time t $Q_i(t) > 0$ then $K_i(t) = 0$ and vice versa.

In addition to the prosumers' production, the community can eventually own productive asset and produces $K^{cer}(t)$ at time t. In this paper, we suppose, to better fit the numerical simulations, that the community has no production asset and that all the energy is produced by the prosumers.

At each time step t, the community consumption is defined as $Q(t) = \sum_{i\in M} Q_i(t)$ and the 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. If the battery is empty at the end of the T periods, we have by definition that $K = H + X$.

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 the 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 the community consumption that is covered by the community production: $\psi = \frac{K}{Q}$. The ratio ψ measures the relative importance of the community production compared to its consumption.

- **The self-sufficiency ratio** (ω) is the percentage of consumption covered by the collective self-consumption: $\omega = \frac{H}{Q}$. It measured the relative importance of the community to satisfy the energy needs of its members.

2.4 The REC and the energy market

We denote by p^m the retail price of energy. 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 members of a community can sell their surplus to the grid at this price p^x. In our model, all prices are time-invariant 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 [1].

2.5 Community costs

The community incurs two different types of costs. On the one hand, a community should be created as a legal entity and there are administrative costs. These costs include the information to the members, the contracting process, the sharing of energy, the preparation the bills, etc. 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 $\bar{C}$.

2.6 The community contract

The REC proposes a contract to households interested in joining the community. The community contract 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 paid to join the community and (4) a sharing rule 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 $\sum_{i \in M} \alpha_i = 1$.

2.7 Profits and benefits

The profit of the community is defined as

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

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

The individual benefit B_i of participating in the community is given by the following equations, the first for the prosumers, 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 have a benefit as they buy the electricity sold by the community at a price p^s instead of the market price p^m. Prosumers have an additional benefit as they sell their production surplus at a price p^p to the community instead of selling it to the market at price p^x.

[1] See Brugel (2022) and CWaPE (2023) for grid fee reduction in Brussels and Wallonia, Belgium

The total benefit for the members is:

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

The community should operate on a non-negative profit basis and guarantee a non-negative benefit for each member. This means that the community contract should satisfy the 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. This is equivalent to

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

This equation defines the total value created by the REC, and this value (if positive) will be shared among the members and the shareholders. Notice that this value is independent of the community contract, the internal prices (p^s and p^p), the sharing rule and the membership fee have no impact on the value created. They are just instruments to redistribute value among members and shareholders.

3 Sharing value inside the community

Equation 5 defines the value created by the community, value that must be shared among the participants. For that, the community has multiple instruments, the sharing rule to allocate self-consumption among members and a system of internal prices, composed of three elements p^s, p^p and F.

3.1 Sharing value: equality v. efficiency

The energy sharing rule and internal pricing *jointly* dictate how the REC 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 REC, we adapt 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 are endowed with technology that correlates the resource (water) consumption with individual monetary gains. Participants choose among two rules: an *egalitarian* rule that evenly divides the available resource 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 doesn't 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 REC 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 $Gini_B = 0$. We will check when this egalitarian allocation is feasible.

3.2 Sharing rules

The self-consumed energy is sold to members at a discounted price p^s. As this cheap energy 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. First, the volume of self-consumed energy 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 the self-consumed electricity among members is done ex-post for billing reasons. 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 energy 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 energy than its actual consumption: $\alpha_i H(\tau) \leq Q_i(\tau)$.

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

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

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 (section B), we provide a detailed algorithm that outlines how this excess energy is allocated among members using an iterative per capita repartition key.

The prorata repartition key is a sharing rule that allocates to each member a quantity of energy corresponding to its share of consumption:

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

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

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

3.3 Internal pricing

The community defines a system of internal prices composed of

- A price p^s for selling the self-consumed energy,
- A price p^p for buying the energy surplus from prosumers,
- A membership fee F.

The price p^s is used to sell electricity to the members. A lower price increases the benefit of consumers and prosumers and the gain to member i is linked to his share of self-consumed electricity α_i. The selling price cannot exceed the electricity retail price: $p^s \leq p^m$.

The price p^p is used to remunerate prosumers for their electricity surplus and a higher price increases the benefits of the prosumers. The benefit being linked to their production surplus. As prosumers can sell electricity to the grid at price p^x, the buying price should satisfy $p^x \leq p^p \leq p^m$.

Finally, the membership fee is used as an upfront payment from the members and it should cover the cost of the assets. In this case, the membership fee must be such that $F \geq \frac{\bar{C}}{m}$. As an alternative, the community can use third-party financing for its assets. In this case, the previous constraint on F can be relaxed.

3.4 Feasible communities

To conduct our analysis, we will suppose that the membership fees cover the cost of storage and the operational cost. 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 equation 6, we can derive the zero-profit constraint which is a locus of prices (p^s, p^s) along which the profit is equal to zero. This locus is given by the following equation and represented by the red line on Figure 2:

$$p^s = p^x + \delta + (p^p - p^x)\frac{K}{H} \tag{9}$$

The locus is increasing with a slope equal to $\frac{K}{H} = \frac{1}{\phi} > 1$; if the community pays more to buy electricity from prosumers, it should sell at a higher price the self-consumed electricity. We define the two extreme points of the locus as $(\underline{p}^p, \overline{p}^s) = (p^x, p^x+\delta)$ and $(\overline{p}^p, \underline{p}^s) = (p^x+(p^m-\delta-p^x)\phi, p^m)$. All the price combinations in the red triangle of Figure 2 guarantee a non negative profit to the community.

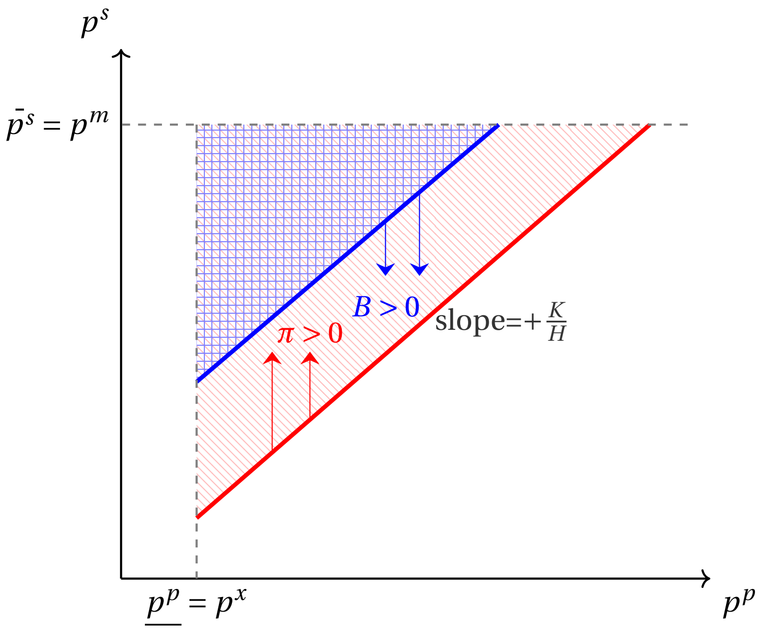

Figure 2: Set of possible prices p^s and p^p

Similarly, from equation 7, we can define a locus of prices guaranteeing a zero benefit to the members:

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

The locus is represented by the blue line on figure 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 $p^m - \frac{\bar{C}}{m} \geq p^x + \delta$, that is if $V \geq 0$. The set of feasible communities is the intersection between the blue and the red areas. As we have said above, this set is non-empty under the condition $V \geq 0$.

3.5 Individual participation constraints

But a positive aggregate benefit does not imply that all consumers participate to the community and we need to add individual participation constraints. In other words, $B \geq 0$ does not guarantee that $B_i \geq 0$ for all $i \in M$. We look at these constraints for the two main sharing rules, per capita and pro-rata consumption.

3.5.1 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[2] $B_i = (p^m - p^s)\frac{H}{m} - \frac{\bar{C}}{m}$ and B_i is positive if:

$$p^s \leq p^m - \frac{\bar{C}}{H} \tag{11}$$

This constraint puts further restrictions on the set of feasible contracts, but the set of feasible contract 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 in turn reduces their benefit and it strengths the above participation constraint.[3]

3.5.2 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. So, individual participation constraints are more complicated to be satisfied. 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:

$$p^s \leq p^m - \frac{\bar{C}}{H}\frac{\underline{\alpha}}{m} \tag{12}$$

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

3.6 The choice of a community contract

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

In particular, if the community wants to achieve an equal repartition 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,

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

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

be it a prosumer or a consumer, would have the same benefit. And increasing p^p above p^x would only be used if prosumers do not receive the same share of the self-consumption than the consumers i.e. p^p could be used to increase the benefits of the 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[4] and there are little advantage of using a pro rata sharing rule. If the community uses of a pro rata sharing rule, the benefit of self-consumption should be large enough.

4 Numerical simulation

4.1 Data

4.1.1 REC organization and energy flows

We use the data from a virtual energy community located in a suburban neighborhood in Belgium. The data come from simulations conducted by ENGIE Laborelec. The community is constituted of 29 members among which 19 are traditional members (consumers), and 10 are prosumers who, together, have solar panels of 52 KWp. Nine members own electric vehicles (EVs). The community does not produce electricity but uses a battery of 75 KW power and 150 KWh capacity [5]. EVs are considered as individual storage systems and the battery is used as a collective storage system for all members. There are 30 meters, 29 for members, and one for the REC battery. The meters of the prosumers record the consumption ($Q_i(t)$) and the injection ($K_i(t)$).

The dataset encompasses one year of simulated energy flows of households forming the REC. It includes data on energy consumption, production export, and storage, all recorded in kilowatt-hours (KWh) through smart meters for each individual member (i) in 15-minute intervals over the course of the year. This amounts to a total of 35,040 time steps. Members' indexes are determined by their type and by their annual consumption such that $i = 1,2,...10 \in M^p \mid Q_1 \leq Q_2 \leq ... \leq Q_{10}$ and $i = 11,12,...29 \in M^c \mid Q_{11} \leq Q_{12} \leq ... \leq Q_{29}$. Members' annual energy flows are summarized in MWh in Tab. 1.

Table 1: Members' annual energy 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

[4] 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.

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

4.1.2 Market prices and costs

The following table contains the market price we use for this study and the asset and the operating costs. For the battery, we compute the levelized cost of storage (LCOS)[6]. The operational cost is equal to €0.05 per kWh self-consumed and it is included in the cost $\bar{C}$.

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	Tariff applied in a REC
$\bar{C}$	€3,979.74	

4.1.3 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 and only 1.19 % is 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 a year. Without storage, only 59.12 % of the production would have been collectively self-consumed. Some performance key indicators are presented in Table 3.

Table 3: REC KPIs and value

Description	Value
Self-consumption ratio ϕ	0.99
Self-production ratio ψ	0.33
Self-sufficiency ratio ω	0.34
REC value V	€1,356.59
Membership fee $F = \frac{\bar{C}}{m}$	€106.20

[6]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

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

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
H_y^s	Energy stored in year y

4.2 Results: 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 done every 15 minutes, the second (static) where the repartition is done on a yearly basis. The repartition of electricity among members is presented in Figures 3 and 4

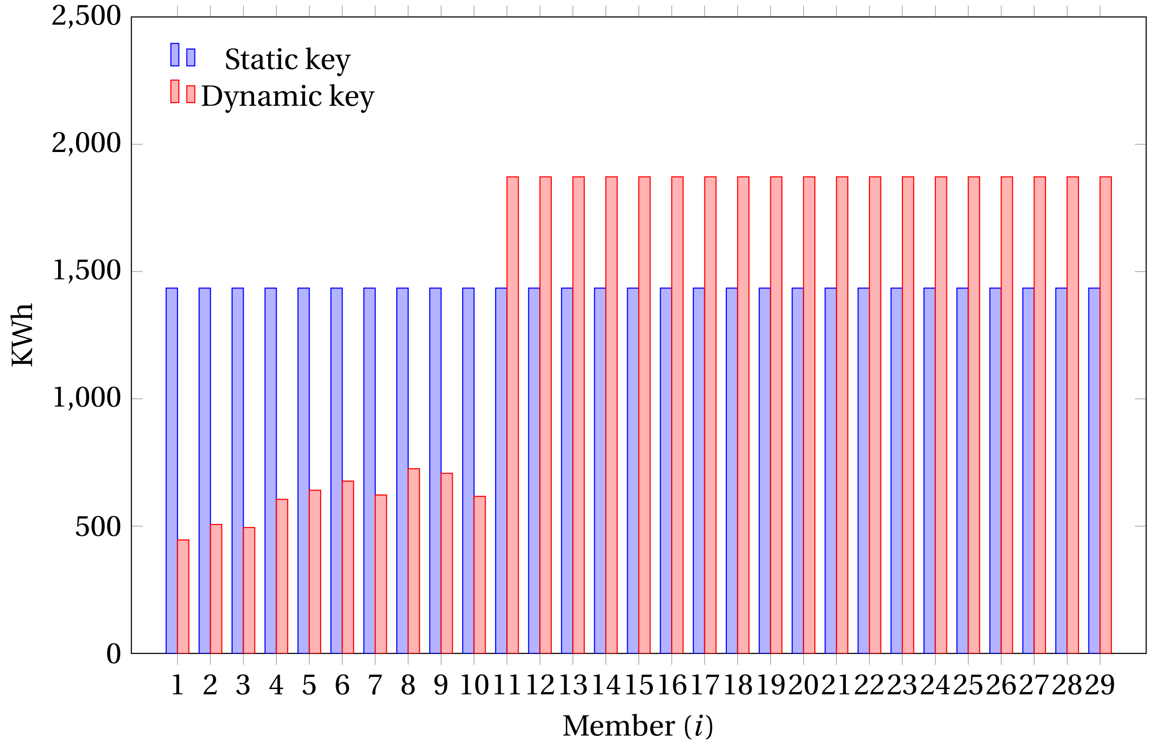

Figure 3: Self-consumption for per capita key: static vs dynamic

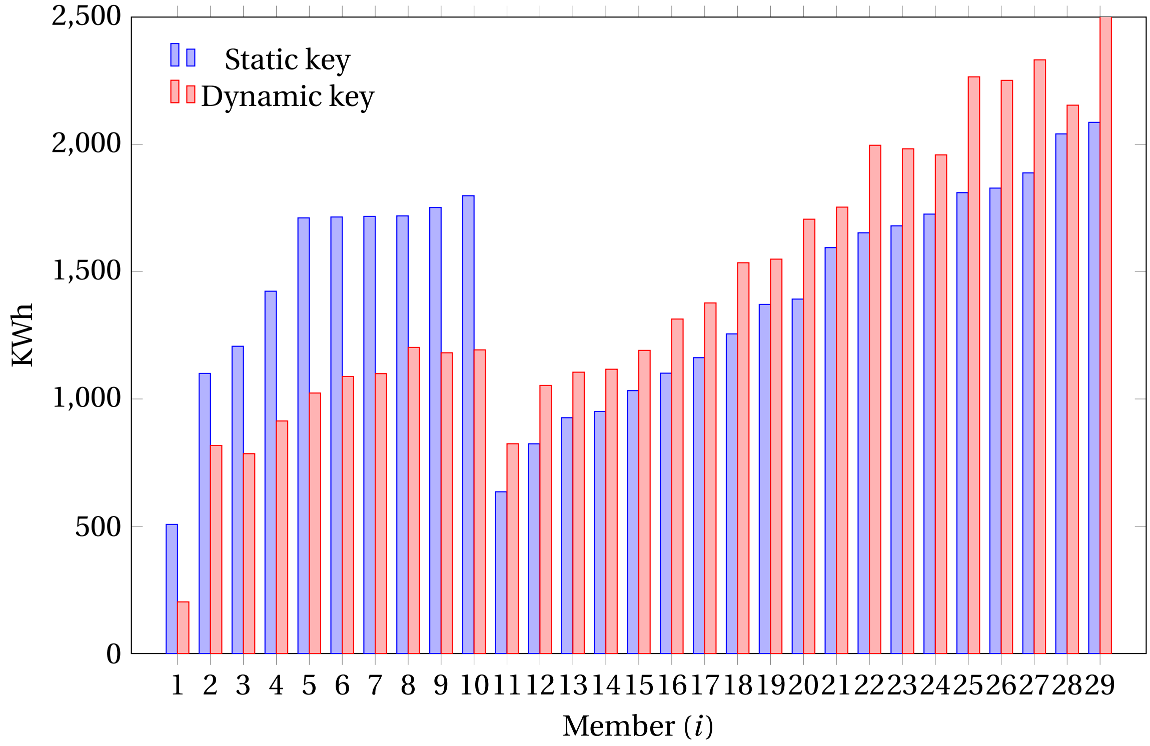

Figure 4: Self-consumption for pro rata key: static vs dynamic

The sharing rules provide different individual self-consumption to each member, and therefore affect the extent at which each member's need in energy is covered by REC energy. 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 (T=1).

On an annual basis, the per capita rule distributes 1,434.84 KWh to all members. In contrast, on a time step basis, it allocates different energy amounts to prosumers, ranging from 445.87 KWh to 725.76 KWh, and assigns a fixed 1,872 KWh to each consumer. The discrepancy in self-consumption among prosumers arises from the fact that during certain production periods, some prosumers have a surplus and therefore they are not eligible for self-consumption.

4.3 Results: admissible prices

We assume that the whole REC value which amounts to €1,357 is distributed in the form of tariff advantages[7]. This implies that there is no profit left to be shared as a dividend. Therefore, all possible price sets are located on the red line in Fig. 2.

For the four sharing rules, we identify the set of prices p^s, p^p such that all the participation constraints are satisfied. All these prices combinations lie on the zero-profit line. We represent these prices on Figure 5.

[7]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.

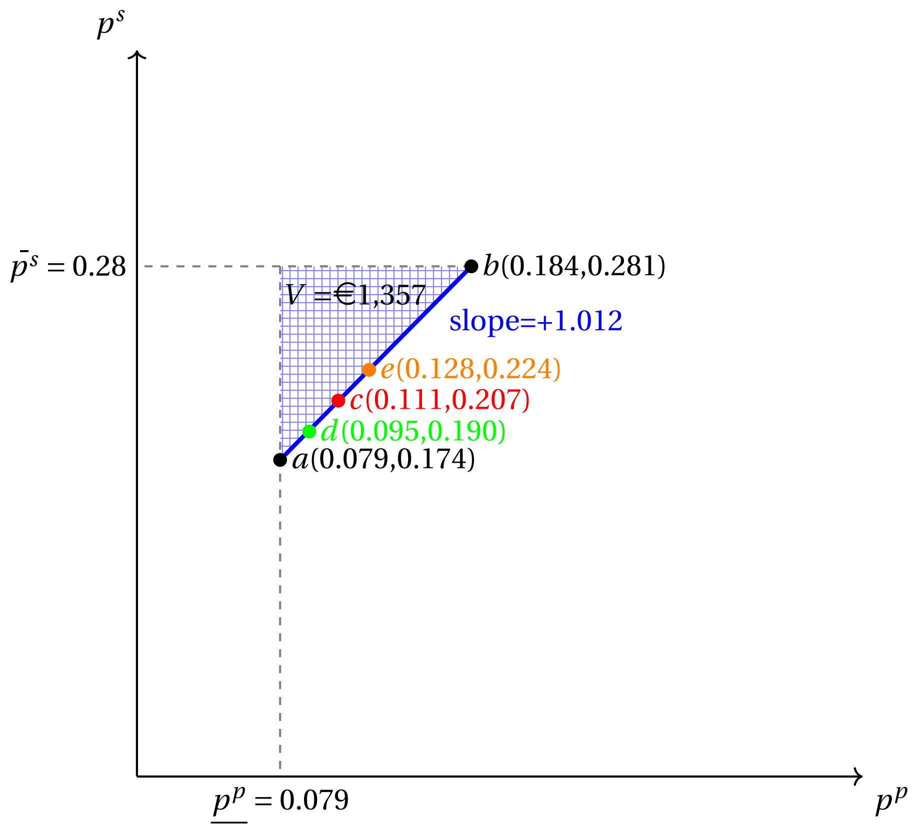

Figure 5: Set of possible prices p^s and p^p in €/KWh

For the static per capita sharing rule, price should be within the range from point a (0.079,0.174) to point c (0.111,0.207). Beyond set c, an increase in p^p induces a rise in p^s which results in a self-consumption gain that can be smaller than the membership fee for traditional consumers. Notice that, with such a rule, all members are allocated the same self-consumption. Therefore, a totally egalitarian solution can be achieved by choosing the lowest possible p^s and a price p^p equal to the market price, $p^p = p^x$, that is point a on the figure.

If the per capita sharing rule is dynamic per capita, prosumers receive less self-consumed energy than prosumers. Consequently, point a above is no longer feasible, some prosumers having a negative surplus. To satisfy the individual participation constraints, the REC should increase the price paid to prosumers and increase the price p^s to maintain the busget balanced. The set of feasible prices lie between d (0.095, 0.190) and e (0.128,0.224). O

Things are more complicated with the pro-rata sharing rule, and it is not possible to find prices such that all participation constraints are satisfied. If the prices are set at point a, prosumers receive the market price for their surplus and they have a benefit only from self-consumption. But the self-consumption of the smaller members is insufficient to cover the fixed fee. To illustrate, with the static sharing rule, members 1 (prosumer) and 11 (consumer) would loose respectively €57 and €38. Increasing the price p^p would make member 1 better off, but member 11 would loose even more. At the same time, high consumption profiles, like member 10 (prosumer) or 29 (consumer) have a large benefit, respectively €86 and €116. Using a dynamic sharing rule would be even worse, at least for member 1.

In our example, it is not possible to implement a pro-rata sharing rule, at least with a constant membership fee. The REC can use menu pricing and offered differentiated fees for the 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 REC can use a mixed sharing key, making the redistribution of the self-consumed electricity more egalitarian.

4.4 Results: equality v. efficiency

Finally, we show that an egalitarian sharing rule does not necessarily lead to an egalitarian sharing of the benefits. Inequality could be created by prices, especially between prosumers and consumers and among prosumers.

To illustrate, let's assume the scenario in which the community chooses the dynamic per capita sharing rule for which the corresponding admissible pricing sets are located between point d (0.095, 0.190) and e (0.128,0.224). From an individual self-consumption perspective, consumers benefit more than prosumers. However, when looking at individual benefits, the outcome depends on the chosen pricing set. Figures 6, 7, and 8 illustrate the individual net benefits achieved by each member when the pricing sets are d (0.095, 0.190), c (0.111, 0.207), and e (0.128, 0.224). The Gini indexes associated with pricing sets d, c and e are 0.25, 0.24 and 0.72, respectively. If the community aims for fairness in the value sharing scheme, the manager would apply pricing set c, as it results in the most equitable distribution of the REC's created value. Conversely, if the community aims to compensate prosumers, the manager would opt for set e. It is also possible that the community opt for the middle set, c, which is fairer than efficient, given that the chosen sharing rule favors consumers for self-consumption. The individual benefit inequality can be observed through the Lorenz curves in Figure 9.

In essence, the most equitable pricing set, d, minimizes the disparity between members, while point e, maximizes prosumers' benefits . Consumers would prefer the lowest pricing set, d, as it provides each of them with a €63 benefit, while prosumers would favor the highest pricing set, e, as it results in an average individual benefit of €135. Finally, the REC manager might apply the middle set c, which is fairer than efficient, given that the chosen sharing rule favors consumers.

5 Conclusion

In spite of their multiple benefits' promotion, RECs remain not fully esteemed by citizens. This is due to the lack of clear added value they can bring. This paper measures the value of REC within the energy system. Two key elements are necessary to justify RECs' implementation and

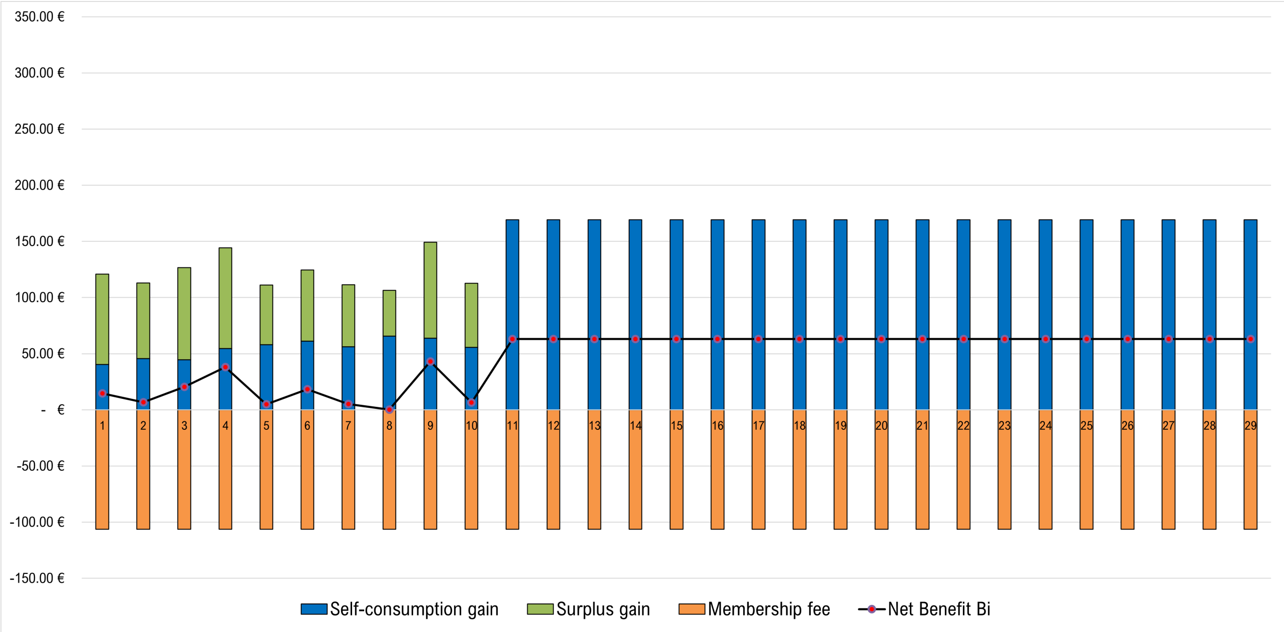

Figure 6: Benefits with the pricing set c (0.095,0.190)

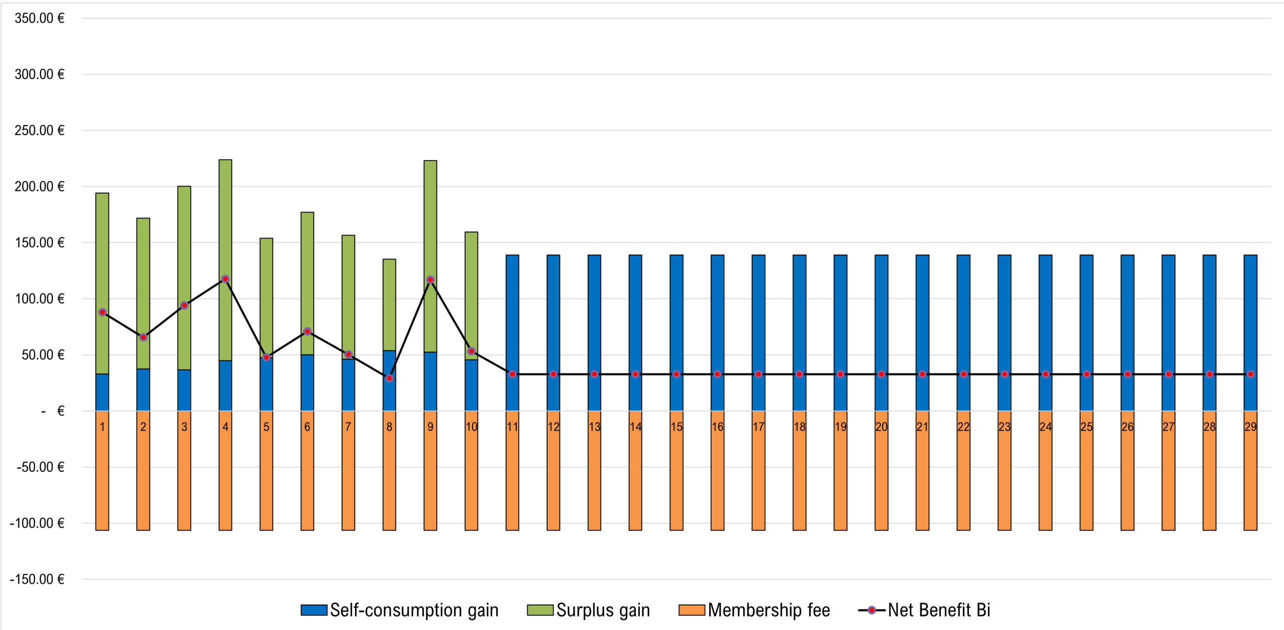

Figure 7: Benefits with the pricing set d (0.111,0.207)

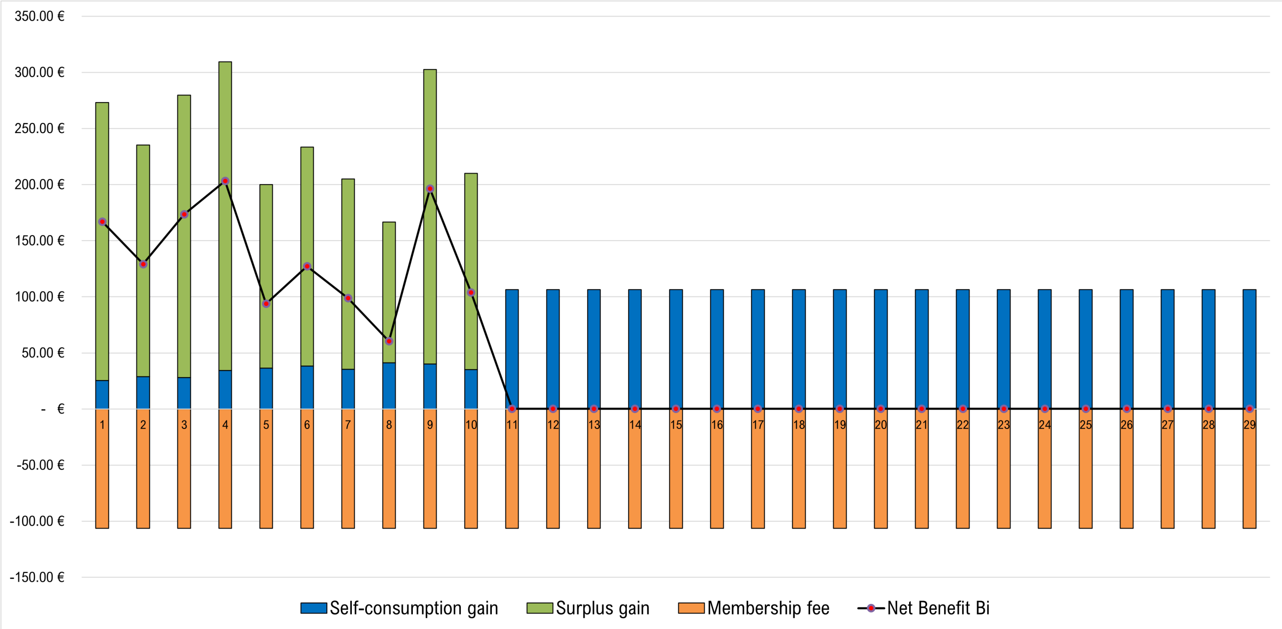

Figure 8: Benefits with the pricing set *e* (0.128,0.224)

replicability: (1) the special status of REC energy compared to the market energy, and (2) the individual benefit for the participating of members. The first element implies that the renewable energy produced and shared within the REC thanks to DPUs is cheaper compared to the energy purchased from retailers on the energy market. The second element responds to the citizen's *what do I get?* question. To respond to the latter, we model simple repartition keys that can be proposed to share energy produced in the community. We also model the tariff setting that grants a positive economic outcome when one joins a REC. The community is composed of members of two types: prosumers who consume and produce energy thanks to their DPUs such as PV panels, and consumers who can join the REC and benefit from cheaper energy. All members have specific consumption profiles. The method to redistribute the REC value among participants of different types and profiles is not straightforward. In order to redistribute that value, this study proposes two tools: energy-sharing rules and the tariff scheme. This analysis underscores the intricate interplay between energy sharing rules and pricing mechanisms. While a particular sharing rule may favor a member based on its characteristics and profile, the selection of a pricing set can exert a substantial influence on an individual's benefits relative to other members. Ultimately, the individual outcomes are contingent upon the prevailing objectives of the community, which may prioritize value distribution guided by principles of equity, seeking to achieve the most even benefit distribution, or prioritize efficiency, which tends to allocate more benefits to those investing in production assets.

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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
   (a) If $Q(t) \geq K(t)$, $X(t) = 0$ and $\Delta S(t) = -(Q(t) - K(t)) < 0$
   (b) If $Q(t) < K(t)$,
      i. If $S(t) + (K(t) - Q(t)) < \bar{S}(t)$, $X(t) = 0$ and $\Delta S(t) = (K(t) - Q(t) > 0$
      ii. 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 $\Delta S(t) = \bar{S}(t) - S(t) > 0$

B Per capita repartition key

The repartition key works along the following algorithm:

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

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:

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

C Graphs

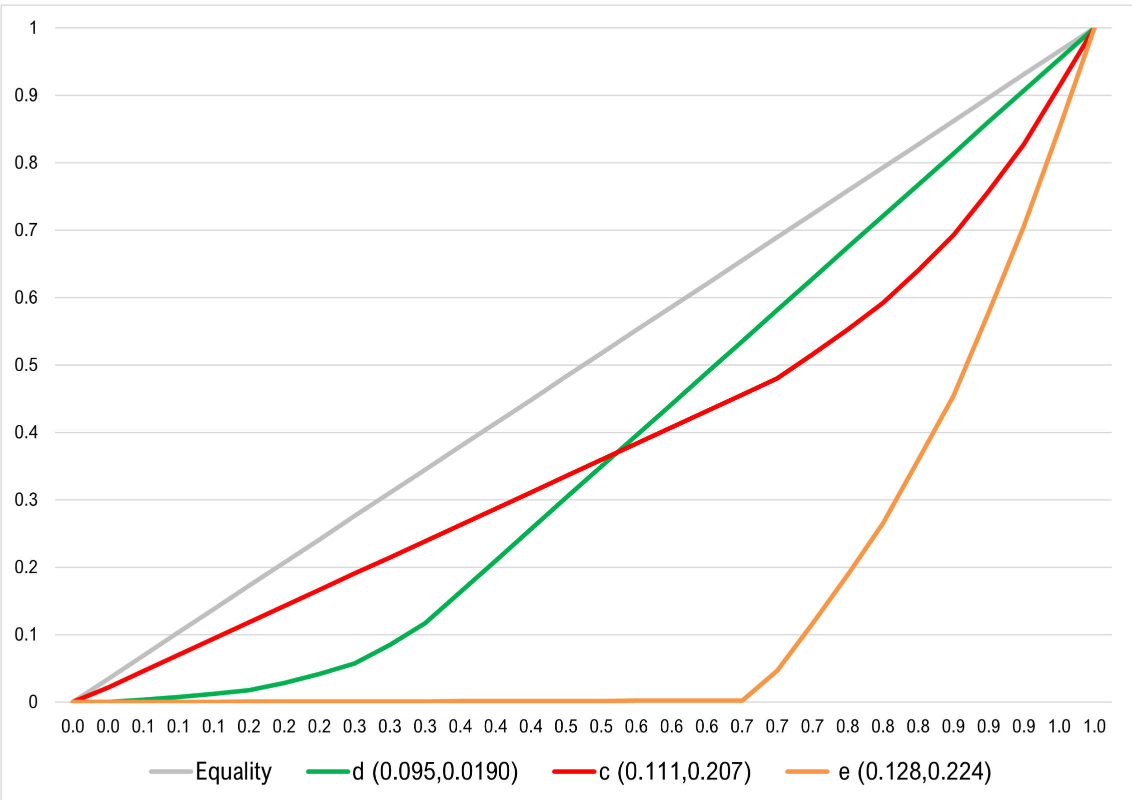

Figure 9: Net individual benefit Lorenz curves by pricing set