Resource and Energy Economics 82 (2025) 101480

Contents lists available at ScienceDirect

Resource and Energy Economics

journal homepage: www.elsevier.com/locate/ree

The energy community and the grid☆

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ARTICLE INFO

JEL classification:
L3
L94
Q48

Keywords:
Energy communities
Decentralized production units
Grid regulation

ABSTRACT

Energy communities involve various agents who decide to invest in renewable production units. This paper examines how these communities interact with the energy system and can decrease its overall cost. First, we show that an energy community can contribute positively to welfare if the electricity produced by the investment is consumed close to its place of production, *i.e* if the community has a high degree of collective self-consumption. Second, our analysis identifies the condition on prices and grid tariffs to align the community's interest with welfare maximization. We also show that some of these grid tariffs do not have a negative impact on non-members of the community and could therefore limit potential distributional issues. Third, various internal organizations of the energy communities are feasible. We show that the internal organization impacts the distribution of benefits among members but not the investment and the global efficiency of the community.

1. Introduction

It is nowadays common to see individuals producing their own electricity with a decentralized production unit (DPU), typically solar panels on their rooftop. For individuals, a DPU generates two types of financial benefits: revenues from power exchanges with the grid and savings on the electricity bill as part of their production is self-consumed. Recently, the concept of self-consumption has been extended from the individual to the collective scope. The idea is that citizens, firms and organizations, located in the same neighborhood can form a community and invest collectively in renewable production units using wind or sun as an input. The energy that the community produces can be shared and consumed locally by the members. These power exchanges can be measured and reconstructed with the metering system and are referred to as collective self-consumption.[1]

☆ The authors thank participants at the conference ''Renewable Energy Communities, Prospects and Challenges'' (HEC Liege, 2022), NEOMA workshop on Decentralized Energy Systems (Paris, 2023), conference JMA (Strasbourg, 2023), AFSE annual congress (Paris, 2023), IBEO workshop (Corte, 2023), EARIE Annual Conference (Roma, 2023), IAEE European Conference (Milan, 2023), FAERE Annual conference (Montpellier, 2023) and seminar participants at HEC Liege, University of Antwerp, University of Paris-Nanterre, University of Sassari and University of Rouen. We thank the Walloon Region (Grant AMORCE) and Métropole Rouen Normandie (CER@R) for their financial support. We are also very grateful to the co-editor (David Brown) for his conscientious and constructive guidance, as well as three reviewers for their helpful comments and suggestions.

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[1] Energy communities differ from peer-to-peer trading platforms in at least two dimensions. First, the community jointly owns assets, production units and batteries, while on peer-to-peer platforms, assets are owned individually by the participants. Hence, they share rather than trade the energy produced. Second, for renewable energy communities, power exchanges among members should have a local dimension.

https://doi.org/10.1016/j.reseneeco.2025.101480
Received 21 May 2024; Received in revised form 15 January 2025; Accepted 16 January 2025
Available online 23 January 2025
0928-7655/

Collective self-consumption can be implemented via an energy community.[2] One type of energy community is defined as a legal entity that invests in a DPU and sells its energy production to its members and any excess to the market. Local exchanges inside the community take place on the public grid. As for individuals, the community generates value from collective self-consumption and from power exchanges with the grid. And these power exchanges should be organized and regulated. Gautier et al. (2018, 2021) investigates exchanges by individual prosumers and the grid. This paper focuses on exchanges by an energy community, with the additional complexity that these transactions should be organized with the grid but also internally among members. Our paper intends to model these two types of interactions.

Communities bring economic and societal gains, but they also disrupt the existing electrical system, which was designed long before they appeared. Their overall efficiency depends on the costs they eliminate, but also on new costs they impose on society. Whether these communities will emerge naturally and be integrated into the energy system by bringing along system-wide benefits remains unclear.

We show that a community creates value for the system as a whole if its collective self-consumption rate is high enough and we identify the optimal investment in production capacity. This first-best can be decentralized if grid and energy prices are cost reflective. In this case, the community creates enough value to ensure the participation of all members. On the contrary, if the retail market is imperfectly competitive, too many communities and too many capacities will be installed. Likewise, if carbon is not correctly internalized, some welfare-improving communities will not emerge and renewable energy communities will install too few production capacities. Finally, we identify a set of regulated grid prices that ensures efficient investment and that do not impact non-members, henceforth limiting distributional issues.

Communities organize themselves and decide on the size of their investments in production assets and on a set of rules and prices to redistribute the value created among the members. In our model, we show that these two fundamental decisions can be dissociated. On one hand, members are unanimous in the choice of the production capacity, but, on the other hand, they disagree on the re-distributional aspects, that is on the prices and the repartition key that the community uses to share the electricity it produces and ultimately the value created among members. For this reason, the internal organization of the community does not matter to determine the investment, an essential element to align the interest of the members with those of the society. Finally, in our baseline model, we consider that the community invests in a single production technology (like solar). As an extension, we consider multiple production technologies and the possibility to store electricity to increase the collective self-consumption.

In the following section, we provide a review of the literature and the policy context. Section 3 introduces our model with a focus on grid fees and energy prices in Section 4. The first best is derived in Section 5. In Section 6, we describe the decentralized outcome and the conditions under which it coincides with the first best. The internal organization of the community is examined in Section 7. In Section 8, we examine the impact on our results of taking into account energy prices that do not reflect actual costs. We extend the model to multiple production technologies in Section 9 and we provide a simple extension to storage in Appendix C. Section 10 concludes the paper. A nomenclature of all variables used in the paper is provided in Appendix D, while all the proofs can be found in Appendix A.

2. Literature and policy framework

2.1. Literature review

This work is related to the economics literature contributing to a successful energy transition (see Fabra and Reguant (2024) for a general discussion). Specifically, our paper ties into studies on incentives for individual investment in distributed generation and its integration into regulated energy systems. Brown and Sappington (2017) look at whether a net metering system can optimally connect prosumers to the grid. They conclude that it is unlikely and that it can create distributional issues between investors and non-investors in distributed generation units. Gautier et al. (2018) argue further that a net purchasing system, where the price of electricity imports and exports differs, is more suited, in part because it incentivizes self-consumption, such as by encouraging the installation of batteries or load shifting. They identify regulatory environments that provide appropriate incentives for individual investments.[3] Assuming that the decentralized energy produced can be traded with other consumers on a peer-to-peer energy trading platform, Cortade and Poudou (2022) argue that, if households are sufficiently heterogeneous in their load factors, this kind of platform can further promote the adoption of distributed generation units. In contrast to previous studies, we specifically investigate the role of community investment, involving contributions from multiple individuals, in distributed generation and its implications for regulatory frameworks. This collective investment approach alters power flows within the network, thereby contributing to the growing body of literature on decentralized energy systems.

Regarding the integration of communities in the energy system, Abada et al. (2020a) analyze the conditions under which a grid death spiral can occur. They assume that collectively self-consumed energy does not pay for the variable grid component of the bill, necessitating new tariffs for the grid operator to break even. As these higher tariffs incentivize the formation of renewable energy communities, they must be increased to sustain grid financing. The authors argue that this can lead to a snowball effect, especially

[2] Energy communities can have multiple forms and multiple purposes (Dudka et al., 2023).

[3] Building up on this modeling framework, Gautier et al. (2021) generalizes this result to situations where consumers are heterogeneous with respect to their self-consumption rate, implying fixed fees have to exceed the grid operator's fixed costs. Similarly, Cambini and Soroush (2019) focus on a specific case where it is not possible to move away from a net-metering system. They highlight that a multi-part tariff for prosumers (composed of a fixed component and two variable parts reflecting distribution losses and other network costs) allows high penetration rates without creating distributional issues.

if tariffs are volumetric. As Schittekatte and Meeus (2020) for individual prosumers, we identify welfare-improving tariffs that do not impact non-members of the community, which does not impair the social acceptability of renewable energy communities.

Regarding the internal organization of the community, Abada et al. (2020b) focus on how the energy surplus is shared among community participants and whether this sharing can lead to a stable community, utilizing the tools of cooperative game theory. Their main finding is that simple sharing rules tend to generate unstable communities, suggesting that aligning the sharing rule with contributions to the community's value, as demonstrated by the Shapley value, is beneficial. In line with this work, we show that members disagree on prices and sharing rules but we show that the economic feasibility and efficiency of renewable energy communities depends on global factors, mainly collective self-consumption and not on the specific internal organization of the community.

In summary, our paper relates to this recent strand in the literature that focuses on renewable energy communities. Part of this body of work addresses the technical difficulties and solutions for managing these communities. These challenges include the management and billing of energy flows within the community (De Villena et al., 2022), the development of algorithms to improve the redistribution of benefits resulting from investments made by renewable energy communities (Norbu et al., 2021), and optimizing the smart charging of electric vehicles at the community level (Pierre et al., 2022). Other studies take a more economic perspective, examining how communities interact with the broader energy system. For instance, Gonzalez et al. (2022) develop a mathematical model to evaluate the impact of renewable energy communities on the power transmission system. Another significant focus in this literature is the economic challenges related to renewable energy communities. Reis et al. (2021) and Iazzolino et al. (2022) review various business models for these communities, while Hanke and Lowitzsch (2020) and Hanke et al. (2021) assess the extent to which renewable energy communities can support vulnerable consumers. These critical issues are also thoroughly addressed in a collective work coordinated by Loebbe et al. (2022). In our contribution, we focus on how renewable energy communities can emerge in a decentralized manner as a strategy to reduce the overall cost of the energy system, particularly in a context where decarbonization is a high priority.

2.2. Policy context

Community-based energy solutions can take various forms and in countries like Germany and Denmark, such communities have thrived for decades (see Rossetto et al. (2022) for a review). In recent years, policymakers have increasingly prioritized the integration of energy communities into the broader energy transition. According to the IPCC (2022), "Energy communities help increase public acceptance and mobilize private funding". This growing emphasis has led to numerous initiatives aimed at promoting the deployment of energy communities. These initiatives seek to decentralize energy production and actively engage citizens in renewable energy projects.

We focus on a specific form of energy community in which (1) renewable installations are jointly owned by community members, (2) the community members are located close to the installation and (3) the members can collectively self-consume (part of) the energy produced by the community. The European Directive on the promotion and use of energy from renewable sources (European Parliament & Council of the European Union, 2018) defines a legal framework for renewable energy communities (REC). This directive is aimed at "actively promoting self-consumption of energy and local renewable energy communities".[4] Within a local area, as geographically defined by the legislation of member states[5], Renewable Energy Communities (RECs) allow community members to collectively produce and share energy.

In the United States, while no specific federal legislation addresses such initiatives, several states and utilities have encouraged renewable energy projects with a similar localized focus. A prime example is community-owned solar gardens, where members must reside near the installation, such as the projects developed by Cooperative Energy Futures in Minnesota. In this paper, we emphasize how adopting a short supply chain for electricity, enabled by initiatives like renewable energy communities, not only benefits its members but can also bring wider benefits to the energy system by potentially reducing grid costs.

3. Model

We model an electricity system with four categories of actors.

Consumers. We consider a population of n consumers, among which a subset form an energy community. Members of the energy community should be located in the same local perimeter. We denote by N the set of consumers, by M the subset of community members and use the index i to represent an arbitrary consumer.

Energy retailers. They have centralized production units (CPU) and sell electricity to their clients. All consumers, members of the community and non-members, have a contract with a retailer.

[4] It requires member states to transpose this directive into their national and regional legislation. Ines et al. (2020), Frieden et al. (2021), and Felice et al. (2022) discuss and compare some of the recent transpositions of this EU directive.

[5] The physical boundaries of what is precisely meant by local for a community depends on the specific legislation. As discussed by Frieden et al. (2021) for the European context, this definition was fully left to the Member States. For example, members of a REC need to be located in the same municipality in Lithuania or Poland. In Italy, Ireland or Austria, they have to be connected to the same low-voltage transformer stations. In France, the source of consumption must be located within a 2-kilometer radius of the production source.

Energy community. The energy community invests in decentralized production units (DPU) . The DPU are connected to the low voltage grid and they are green substitutes to the CPU. The community sells its production to its members and the surplus to the retailers. The community is organized as a legal entity that is responsible for its internal management (membership, billing, etc.). The community defines a price for the energy it sells to its members, and a sharing rule to allocate energy collectively self-consumed among its members.[6] Importantly, the community is only a partial substitute to the energy retailers and they supply the balance when the community's production is insufficient to cover the members' consumption.

The grid. All the power exchanges, including the exchanges inside the community, use the public electricity grid and there are (regulated) grid fees charged for power exchanges.

3.1. Time horizon and metering technology

The community operates over a given time frame and the relevant period is divided in T time steps (for instance a quarter of hour). The DPU and the consumers are equipped with smart meters that measure for any t in $[0, T]$, the individual consumption and the DPU's production. Real-time meter readings are essential to determine the collective self-consumption as, by definition, it corresponds to the consumption that is synchronized with production. In Appendix B.1, we explain how the collective self-consumption can be constructed from meter readings. For the remaining of the paper, we use consumption and production variables aggregated over the T periods.

3.2. Electricity generation

CPU produces electricity at a cost c per MWh. CPU mainly uses non-renewable production technology and their production have an environmental externality δ per MWh produced with δ proportional to the carbon intensity of centralized generators.

DPU use a renewable energy source (wind or solar). A DPU with capacity $\tilde{k}$ in MW *i.e* a notional maximum production, actually produces $k = \beta\tilde{k}$ MWh, where β is the capacity factor.

The cost per unit of capacity is $\tilde{z}$. The cost per MWh can be expressed as $z = \frac{\tilde{z}}{\beta}$ *i.e* it costs zk to produce k MWh.

3.3. Electricity consumption

Each inhabitant $i \in N$ has a given consumption q_i. We will denote by $Q_M = \sum_{i \in M} q_i$ the total consumption of the community members, by $Q_{NM} = \sum_{i \in N \setminus M} q_i$ the total consumption of the non-members and $Q = Q_M + Q_{NM}$.

3.4. Collective self-consumption

Collective self-consumption within the community refers to consumption by the members of the energy produced by the DPU, with production and consumption being synchronized. We denote by h, the collective self-consumption.

The community's self-consumption depends on, firstly, the synchronization between the production and the consumption profiles, secondly, on the production level itself. For that reason, we will denote the aggregated self-consumption of the community by $h(k)$ and we will suppose that it can be represented by a function $h(k)$ that is continuous and differentiable and we assume the following:

Assumption 1. $h(k) \leq k$, $h'(k) \geq 0$ and $h''(k) \leq 0$.

The first part means that self-consumption cannot exceed production (by definition)[7] implying $h(0) = 0$, the second part means that self-consumption increases with production but at a decreasing rate. We will denote the self-consumption rate of the REC by $\varphi(k) = \frac{h(k)}{k}$, the self-consumption rate is the percentage of the energy produced by the community that is consumed by its members. We can establish that:

Lemma 1. *$\varphi(k)$ is non-increasing in k.*

This result is a direct consequence of the concavity of self-consumption volume. It is also empirically well-founded. Based on an applied analysis of PV systems in Italy, Lazzeroni et al. (2021) find that the self-consumption rate decreases with PV size. For individual prosumers in average, it drops from 72.34% to 16.01% when the PV size increases from 1 to 6 kWp. In Appendix B.2, we provide further empirical evidences to illustrate Assumption 1 and Lemma 1.

[6] Note that all these steps can be carried out with the assistance of a facilitator, who helps set up the association, manages the installation, provide phone apps to track energy flows, and handles the community's internal billing, among other tasks.

[7] For low levels of k, we may have that $h(k) = k$ and $h'(k) = 1$. But above a certain capacity level, we will move to a region where $h(k) < k$ and $h'(k) < 1$. We will show that the welfare maximizing level lies in this last region.

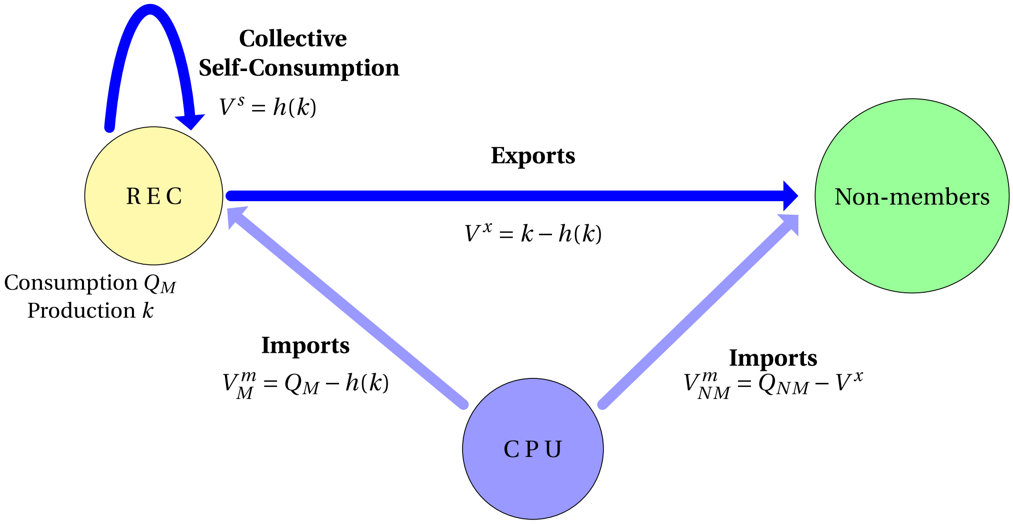

Fig. 1. Power Exchanges.

3.5. Power exchanges

All the power exchanges take place on the public electricity grid and the community has no network infrastructure on its own. Different types of power exchanges are represented in Fig. 1. First, power is supplied by the CPU to the community when the community's production is insufficient to cover the consumption and to the other inhabitants outside of the REC. We refer to this as an *import* from the grid and denote the total volume (in MWh) of import by V^m. Second, when the community's production exceeds its consumption, the power surplus is sold to the retailers, who later sell this energy to consumers outside the community. We refer to this as an *export* to the grid and denote the export's volume by V^x. Exports from the community reduce the import of the non-community members, and therefore the CPU production. Finally, the members consume part of the energy produced by the community. We refer to this as the *collective self-consumption* and denote the self-consumption volume by V^s.

Using the definition, we can identify the volume of the different power flows on the network. For the import from the CPU, we distinguish the import from the community (V^m_M) and the imports from the non-community members (V^m_{NM}) that will consume the surplus of the DPU (V^x) instead of importing from CPU.

$$\begin{aligned}
V^s &= h(k), \\
V^x &= k - V^s = k - h(k), \\
V^m_M &= Q_M - V^s = Q_M - h(k), \\
V^m_{NM} &= Q_{NM} - V_x = Q_{NM} - (k - h(k)), \\
V^m &= Q - k.
\end{aligned}$$

4. Grid fees and energy prices

4.1. Grid costs

The grid connects all consumers and centralized production units. The grid has two types of costs, a fixed cost per user (F) and a variable cost per MWh distributed. The variable cost includes all the current and future network developments that should be undertaken to cope with power exchanges, including injections by the DPU.

We suppose that the variable cost is specific to each power flow and denote by θ^m, θ^x and θ^s, the cost per MWh associated with imports, exports and self-consumption respectively. We suppose that the grid cost associated with the DPU differs depending on whether the electricity is locally self-consumed or exported, with the idea that massive power injection on the low-voltage grid requires network reinforcements and upgrades expenditures. These additional costs are mostly due to the historical design of power systems developed as "one-way" from producers to consumers. They include additional investments in on-load tap changers, booster transformers or static volt–ampere reactive compensators to accommodate the greater variations in voltage (Shivashankar et al. (2016). Furthermore, local power exchanges reduce power losses. Consequently, we make the following assumptions on production and grid costs. First, following the previous discussion we assume:

Assumption 2. $\theta^x > \theta^s$.

Second, we suppose that the DPU are not an efficient substitute for the CPU to serve non-local consumers.

Assumption 3. $c + \delta + \theta^m < z + \theta^x$.

This assumption is compatible with a lower generation cost for DPU ($z < c$) and says that the grid costs of injecting production of the DPU for non-local consumers do not compensate the eventual cost savings. In other words, it is not efficient for energy retailers to invest in DPU.

Third, we assume that production by a DPU is preferred to production by a CPU if the energy is self-consumed.

Assumption 4. $c + \delta + \theta^m > z + \theta^s$.

Together, these assumptions imply that the DPU will be preferred to the CPU if the self-consumption rate is high enough.

The total distribution cost is equal to[8]

$$C_d = \theta^m V^m + \theta^x V^x + \theta^s V^s + nF = \theta^m (Q - k) + \theta^x (k - h(k)) + \theta^s h(k) + nF. \tag{1}$$

4.2. Grid fees

Overall, grid operators tend to be regulated. Regulators specify a tariff for the grid and define a methodology to set the tariff level. There is a variety of practices and instruments to regulate grid operators. In this paper, we will consider that the fees set by the regulator should cover the total grid costs C_d.[9] In addition to cost recovery, the regulator may have other objectives, such as efficiency or fairness and we discuss some of them through the paper.

We consider two types of fees: a fixed fee (ψ) per user and a variable fee per MWh. This variable fee can be specific to each flow and denote by ρ^m, ρ^x and ρ^s the fee applied for imports, exports and self-consumption.[10]

The following equation identify the grid fees satisfying the *cost recovery principle* for the operator:

$$\rho^m V^m + \rho^x V^x + \rho^s V^s + n\psi \geq C_d. \tag{2}$$

Network tariffs have an impact on community members and non-members. In particular, Abada et al. (2020a) shows that, following the formation of a community, the grid tariff should be modified to recover the grid cost. This, in turn, impacts the number and the size of the communities and non-community members. And this of course is a concern as communities possibly exert externalities on non-members.

To avoid transferring the burden of the grid costs to non-members, we can add a constraint in the tariff design to guarantee that the formation of a community has no impact on the bill of citizens outside of it. We call this the *neutrality to non-members principle*.

Without community, the grid's budget balance constraint would write

$$\rho^m Q + n\psi \geq \theta^m Q + nF,$$

and this determines a grid tariff locus (ρ^m, ψ) such that

$$\rho^m = \theta^m + n\frac{F - \psi}{Q}. \tag{3}$$

Any point on this locus guarantees that the grid budget is balanced in the absence of a community. Non-members will not be affected by the creation of any REC if the regulator maintains the same tariff when communities form.

In our analysis, we will consider different grid tariffs but we will use as a benchmark, the so-called cost-based or Coasian tariff, defined as follow.

Definition 1. A Coasian tariff is a two-part tariff where the fixed part is set to the fixed cost $\psi = F$ and the variable parts are set to the variable costs $(\rho^m, \rho^x, \rho^s) = (\theta^m, \theta^x, \theta^s)$.

With a Coasian tariff, the prices paid by the users fully reflect the induced costs and the grid has a balanced budget, that is (2) is fulfilled. Note that a Coasian tariff belongs to the locus (3).

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[8] Note that the costs of the grid are also driven by the peak demand and the community may reduce the peak demand from CPU by producing and selling its own electricity to its members at peak time. In this case, the community brings an additional benefit to the system. In our model, this could be integrated by considering that there is an additional capacity cost in the grid cost C_d, this capacity cost could be related to the volume of electricity imported and could be written as $\theta^c V^m$. The capacity could be recovered by a capacity fee and the analysis can be replicated similarly.

[9] Providing incentives to the grid operator is another important objectives for the regulator but we leave this aside in the paper.

[10] Note that this is a more general assumption than in Abada et al. (2020a,b) who assume that $\rho^s = 0$ *i.e* that collective self-consumption takes place behind the meter, or there is no network fee for collective self-consumption.

Finally, we will adopt the accounting convention that the community pays the grid fee on the self-consumption volume and the retailers pay the grid fees on the imports and exports. The fixed fee is collected by the retailers and directly transferred to the grid.

4.3. Energy prices

Energy retailers sell energy to consumers at a retail price p^m. The energy they sell is either produced by the CPU or bought from the community at a price p^x.[11] The retailers pay the grid fee and there is a carbon tax τ, to compensate for the CO2 emissions of the CPU. The retailers' profit is equal to:

$$\Pi^r = (p^m - \rho^m - c - \tau)V^m + (p^m - p^x - \rho^x)V^x. \tag{4}$$

The first term in Eq. (4) is the profit realized on the electricity produced by the CPU and sold to consumers at the retail price, the second term is the profit realized on the sales of electricity surplus bought from the community at a price p^x and sold to the non-members at price p^m.

We define a competitive market as a market where the energy prices (p^m, p^x) are set to marginal cost. This implies that the retail price is set to equate the cost of centralized production, including network fees and externality correction, and the export price is set to have zero profit on exports.

Definition 2. Competitive electricity prices are defined as :

$$p^m = c + \tau + \rho^m, \tag{5}$$

$$p^x = p^m - \rho^x = c + \tau + \rho^m - \rho^x. \tag{6}$$

5. First best

In this section, we derive the first best investment level for a REC of size m. In our model, consumptions are given and the first best corresponds to the minimization of the total cost for the energy system *i.e* the sum of the generation and the distribution costs.

The total generation cost is equal to

$$C_g = (c + \delta)(Q - k) + zk. \tag{7}$$

A community producing k increases the welfare if the sum of C_g and C_d is lower than the cost of satisfying all the community's consumption with CPU:

$$C_g + C_d \leq (c + \delta + \theta^m)Q + nF.$$

Or put equivalently when the social cost saving $\Delta C(k) = (c + \delta + \theta^m)Q + nF - \left(C_g + C_d\right)$ is positive, that is:

$$\Delta C(k) = (c + \delta + \theta^m - (z + \theta^x))k + (\theta^x - \theta^s)\, h(k) \geq 0. \tag{8}$$

The first term in Eq. (8) is the cost of replacing CPU by DPU if there is no self-consumption. Given Assumption 3, this term is negative. The second term is the benefit provided by having self-consumption instead of exports, a benefit that is linked to the self-consumption level. We can state that

Lemma 2. *A REC increases welfare if $k \leq \bar{k}$ defined as*

$$\varphi(\bar{k}) = \frac{h(\bar{k})}{\bar{k}} = \frac{z + \theta^x - (c + \delta + \theta^m)}{\theta^x - \theta^s}, \text{ with } 0 < \varphi(\bar{k}) < 1.$$

This condition means that a REC increases the welfare if its collective self-consumption rate is large enough. As the self-consumption rate decreases with the production capacity, the lemma defines a maximal capacity for the community. For any $k \in [0, \bar{k}]$, the community positively contributes to welfare.

Next, we can identify the first best production level for the REC. This level results from the minimization of the total cost $C_d + C_g$ with respect to k or equivalently the maximization of $\Delta C(k)$.

Lemma 3. *The welfare maximizing community investment is given by $k^* < \bar{k}$ defined as :*

$$h'(k^*) = \varphi(\bar{k}) = \frac{z + \theta^x - (c + \delta + \theta^m)}{\theta^x - \theta^s} < 1.$$

[11] In practice, feed-in tariffs are progressively being indexed on dynamic market prices. Taking a dynamic price into account would not fundamentally change the result in Lemma 2 below. We would then have to take into account the discounted sum of self-consumption rates and cost ratios.

6. Feasible energy community

We now turn to the question of the feasibility of these communities in a world of exchanges and markets. Member $i \in M$ has a financial benefit if participation to the community reduces its energy bill.[12]

In this section, we identify the benefit B_i of each member, the total benefit of the m members $B = \sum_{i\in M} B_i$ and the profit of the community itself, π. The total value created by the community is $v = B + \pi$ and a necessary condition to make a community feasible is $v \geq 0$. In this section, we analyze when this condition is satisfied. In the next section, we look at the internal organization of the community, to identify how participation constraints could be satisfied ($B_i \geq 0$).

6.1. The community profit

The community will propose to the m potential members to collectively invest in producing k MWh. Members have to pay a membership fee f and, in exchange they will have the opportunity to buy the energy produced by the community at a discounted price p^s. We assume that management costs for the community are set to zero.

The community can only sell electricity to the members when their consumption is synchronized with production *i.e* the community can only sell $h(k)$ to its members and the remaining electricity will be sold to retailers at price p^x.

The profit of the community is given by:

$$\pi = (p^s - \rho^s)h(k) + p^x(k - h(k)) - zk + mf. \tag{9}$$

The community should be profitable to operate. If the community is making profits ($\pi > 0$), these profits could be redistributed to the members either as reduced membership fees or reduced energy price.

6.2. Benefits to the members

The community proposes a sharing rule to share the collectively self-consumed energy between the members. This sharing rule can be done for instance, per capita, pro-rata total consumption, pro-rata synchronized production or according to the individuals' contribution to the community value (Shapley). Abada et al. (2020a) provide examples and discuss the merits of different sharing rules. We denote the sharing rule by $\boldsymbol{\alpha} = (\alpha_i)_{i\in M}$, specifying the share α_i of $h(k)$ that is allocated to member i, with $\sum_{i\in M} \alpha_i = 1$.

A member is willing to participate to the community if the energy bill is lower than without opting in that is if $p^m \left(q_i - \alpha_i h(k)\right) + p^s \alpha_i h(k) + f + \psi \leq p^m q_i + \psi$. This also means that the energy savings on its share of self-consumption, corresponding to $(p^m - p^s)\alpha_i h(k)$ are sufficient to cover the fixed entry cost f. From that, we can define the participation constraint of member $i \in M$:

$$B_i = (p^m - p^s)\alpha_i h(k) - f \geq 0. \tag{10}$$

Summing the participation constraints of the m members and rearranging terms, we obtain

$$B = \sum_{i\in M} B_i = (p^m - p^s)h(k) - mf \geq 0. \tag{11}$$

This condition identifies the communities that create a positive value for their members. If this condition is not satisfied, the participation constraints cannot be fulfilled for all the m individuals.

6.3. Feasible communities

The total value created by a community v is the sum of the members' benefit B, defined in Eq. (11), and the profit π, defined in Eq. (9). A necessary condition for being feasible is to create a non-negative value:

$$v = B + \pi = (p^m - \rho^s)h(k) + p^x(k - h(k)) - zk \geq 0. \tag{12}$$

Eq. (12) says that a community has a positive value ($v > 0$) if the revenue from selling the self-consumed electricity to the members at the retail rate net of the grid fee ($p^m - \rho^s$) plus the revenue from selling the remaining power to the retailers at the export price p^x should be sufficient to cover the cost of decentralized production. If it is the case, the community is feasible. Interestingly, this feasibility condition does not depend on the internal organization of the community: the choice of a price p^s and of a membership fee f, nor the choice of a sharing rule $\boldsymbol{\alpha}$. Eq. (12) can be expressed equivalently as:

$$\varphi(k) \geq \frac{z - p^x}{p^m - p^x - \rho^s}. \tag{13}$$

The feasibility condition only depends on the market prices and the grid fees and the self-consumption rate. It is therefore possible to assess the feasibility of a community based on a single characteristic: the collective self-consumption rate. If the self-consumption rate is high enough Eq. (13), the community is feasible; otherwise it is not.

[12] Even if the literature has shown that they do play a role (see for example (Bauwens and Devine-Wright, 2018)), we leave aside other motivations such as those related to environmental consciousness or social norms related to joining a community.

In a competitive environment with full internalization of the negative carbon externality ($\tau = \delta$) and with a Coasian tariff, competitive prices given in (5) and (6) boil down to the following prices:

$$p^m = c + \delta + \theta^m, \tag{14}$$

$$p^x = c + \delta + \theta^m - \theta^x. \tag{15}$$

Replacing these prices in (12) then the community value is $v = \Delta C(k)$ where $\Delta C(k)$ has been defined in (8), so we can show that:

Proposition 1. *With a Coasian grid tariff and a competitive environment with carbon internalization, only energy communities that increase the welfare are feasible.*

In *full internalization* settings *i.e* Coasian tariffs, competitive environment and carbon internalization, only welfare-improving communities are feasible as they generate a positive surplus for the members and a non-negative profit for the community. Distribution and retail prices play adequately their role in encouraging the emergence of energy communities to invest in renewable, so to lower the costs of the energy system. By making collective self-consumption possible, the community is beneficial to the society as a whole and to its individual members, without impacting the non-members as prices and tariffs perfectly reflect the induced costs.

To a certain extent, the result in Proposition 1 may seem tautological as energy communities appear to be feasible only if they are welfare-improving. Given that non-members are unaffected by the formation of an energy community, one could deduce that the only possible way an energy community could be welfare-improving is if it is profitable to its members. But this is only true if markets and institutions are efficient. As we will show in Section 8, this seemingly circular logic does not apply when benefits and costs are not fully internalized by the community, for instance when retailers have positive margins, network tariffs are not aligned with costs or when carbon taxation is imperfect.

7. Organization of the community

In the previous section, we identified when a community creates value. In this section, we look at the organization of the community and, in particular, how the value v is redistributed. This redistribution should satisfy the individual's participation constraint as members ultimately participate if they have a positive benefit $B_i \geq 0$. When these constraints are satisfied, the community could pursue other objectives and redistribute value accordingly. These pursued benefits can for example be related to the provision of cheaper energy to its members, the fight against energy precarity or the investment in renewable energy sources.

For the main part of our analysis, we will suppose that the community operates as a non-profit and redistributes all the value to its members ($\pi = 0$ and $B = v$).[13]

7.1. Community prices

For a given production k, we can define using Eq. (9), a locus of prices p^s and membership fees f that give a zero profit for the community. For price and tariff (p^x, ρ^s), this locus writes:

$$p^s = \rho^s + p^x + \frac{z - p^x}{\varphi(k)} - \frac{m}{h(k)} f. \tag{16}$$

It is represented in Fig. 2, and it shows a negative relationship between the membership fee f and the energy price p^s. If the community is zero-profit, it must select a point (p^s, f) on this locus to satisfy all participation constraints. By Proposition 1, if such a point exists it also improves social welfare when full internalization is implemented.

A particular point on the locus corresponds to selling the self-consumed energy at the retail price minus ϵ. In this case, there is almost no saving on the energy bill and the member will participate only if it receives a share of the community's profit, that is if $f < 0$. It is straightforward to show that for $p^s = p^m$, we have $f < 0$ if Eq. (13) holds true, as this condition is necessary for a non-empty locus. With such a solution, the community covers its costs with the energy sales and redistributes the surplus as a dividend to its members. Formally, the dividend paid to the members when the community sells energy at the retail price is equal to:

$$\underline{f} = \frac{h(k)}{m}\left(\frac{z - p^x}{\varphi(k)} + p^x + \rho^s - p^m\right) < 0. \tag{17}$$

With such an agreement, all the members derive the same benefit from participating to the community.

Obviously, selling energy at the retail price is not the only feasible agreement. The community can decrease the price for self-consumption and increase the membership fee while keeping its budget balanced. With a lower price, the benefits of the community will be shared differently and they will now also depend on the sharing rule $\boldsymbol{\alpha}$. Consumers with a high allocated self-consumption will have a higher benefit, those with a lower allocated self-consumption will have a lower benefit. The lowest price the community

[13] Note that non-profit RECs were at the heart of the european legal process. Indeed, according to Article 2 (16) of the renewable energy directive (European Parliament & Council of the European Union, 2018), "The primary purpose [of renewable energy communities] is to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits". We will briefly discuss the case of a profit maximizing community in footnote[14].

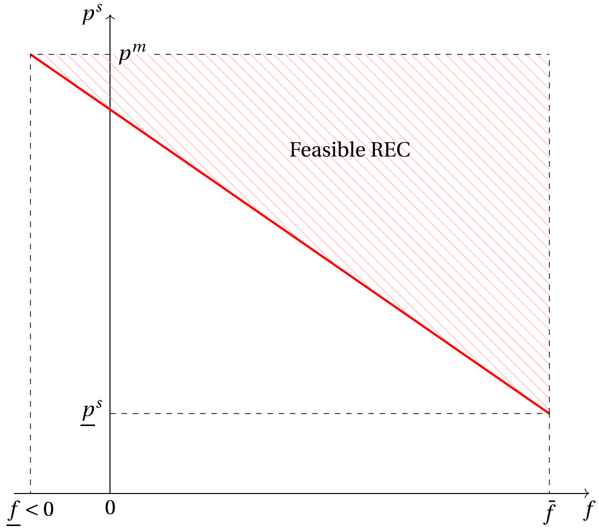

Fig. 2. Possible prices and fees in a feasible energy community.

can achieve will be given by the participation constraint of the member with the lowest allocated self-consumption. Define $\underline{\alpha}$ as the $\min_{i\in M} \alpha_i$ and we suppose that $\underline{\alpha} < \frac{1}{m}$.

From the participation constraint computed for $\alpha_i = \underline{\alpha}$ and the zero profit constraint, we can define the lowest admissible price $\underline{p}^s$ and the corresponding entry fee $\overline{f}$:

$$\underline{p}^s = p^m + \frac{z - p^x}{\left(1 - m\underline{\alpha}\right)\varphi(k)} - \frac{p^m - p^x - \rho^s}{1 - m\underline{\alpha}}, \quad \overline{f} = -\frac{m\underline{\alpha}}{1 - m\underline{\alpha}}\underline{f} > 0. \tag{18}$$

Lemma 4. *The set of possible prices within a feasible community includes $(p^m, \underline{f})$ and $(\underline{p}^s, \overline{f})$ and all the convex combinations of these two points: $p^s = xp^m + (1 - x)\,\underline{p}^s$ and $f = x\underline{f} + (1 - x)\,\overline{f}$, for $x \in [0, 1]$. These prices satisfy the participation constraint of all members.*

7.2. Choice of capacity by the community

The community has to choose a price, identified by a weight x in Lemma 4 and a production capacity k. In this section, we show that these two fundamental decisions for the community can be dissociated. That is the choice of internal prices does not influence the choice of a capacity.

For that, we compute the individual benefit of member i as a function of the prices, that is as a function of 'x'. We can show that.

Lemma 5. *For any prices identified in Lemma 4, the corresponding benefit of member i writes $B_i = A_i(x)\,v$ where*

$$A_i(x) = \frac{\alpha_i m (1 - x) + x - \underline{\alpha} m}{\left(1 - \underline{\alpha} m\right) m} \quad \text{with} \quad \sum_{i\in M} A_i = 1,$$

for any $x \in [0, 1]$.

Lemma 5 indicates that the benefit of member i is the product of two terms. The first, $A_i(x)$ depends on the internal organization of the community and its price system. The second v depends on market prices and the DPU's capacity. As a consequence, the questions of value creation and value distribution can be separated.

Under full internalization, as $v = \Delta C(k)$, each member benefit is simply collinear to the social cost saving $\Delta C(k)$, and all members are unanimous in choosing the first best investment level.

Proposition 2. *With a Coasian grid tariff and a competitive environment with carbon internalization, the community chooses the first best investment level k^*.*

This result[14] is a consequence of both the welfare improvement allowed by feasible RECs when full internalization conditions hold (Proposition 1) and internal prices that redistribute the value to members independently of v (Lemma 5). The pricing rule

[14] In this analysis, we supposed that the community redistributes all the value to its members. Instead if we had supposed that the community wants to maximize profits under the constraint that members participate, this result remains the same. Indeed in such a case, it is possible to extract all the surplus of

leads to select a price-fee couple on the zero-profit constraint, which gives each member a benefit based on a share of the social cost savings brought by the REC. As a result, each member of the REC internalizes the social effect of investing in the DPU and all members end up with individual preferences aligned with the welfare. Consequently, they are all agreeing to select the first best investment level.

7.3. Choice of prices by the community

Now we turn to the choice of price p^s and fee f within the community. We identified above the optimal investment (under full internalization) and the set of possible prices but members disagree on the choice of a particular one. Indeed, for each member choosing a couple price-fee, is equivalent to decide of $x \in [0,1]$ that maximizes the individual benefit $B_i = A_i(x)v$, so we can show that:

Lemma 6. *(i) If $\alpha_i < \frac{1}{m}$, individual i prefers $x^* = 1$ i.e the highest possible price $p^s = p^m$ and a dividend $\underline{f} < 0$. (ii) If $\alpha_i > \frac{1}{m}$, individual i prefers $x^* = 0$ i.e the lowest possible price $p^s = \underline{p}^s$ and a positive entry fee $\overline{f} > 0$.*

Lemma 6 is an essential result concerning the decision rule within the community. It shows that whatever the internal governance or the voting rules used within the community, the pricing decision will be one of the two extreme points on the locus (16).

We have shown that the exact pricing decision in the REC has no impact on the investment decision achieved and therefore the efficiency result when full internalization holds. However, this may impact the benefit level obtained by each member ex-post. The choice of a price depends on the rules governing the organization of the community. For instance, if the REC adopts the 'one member one vote' decision rule, the price would be fixed by the median member's self-consumed energy share, according to Lemma 6.

7.4. Community size

So far, we considered a community of a given size m and we searched for an organization that guarantees that all the m participation constraints will be satisfied. In this section, we discuss the possibility for the community to include additional members, located in the same area.

Consider a community with m members, investing in producing k^m and creating a value v^m. The addition of a new member will increase the community value to $v^{m+1} \geq v^m$, since for any given production level k, the self-consumption level cannot decrease if membership extends: $h^{m+1}(k) \geq h^m(k), \forall k > 0$. So, even if the community does not adapt its investment after including a new member, its value cannot decrease. Let us denote the additional value created by the new member by $\Delta v = v^{m+1} - v^m \geq 0$.

The inclusion of a new member will change the allocation of value within the community. Let us denote by A_i and $\tilde{A}_i$ the share allocated to member i in a community of size m, respectively $m+1$, determined according to Lemma 5. The benefit of the new member can be denoted by $B_{m+1} = \tilde{A}_{m+1} v^{m+1}$. The entry of a new member will not be detrimental to the existing m members if what they get *together* in a community of size $m+1$ is larger than what they get in a community of size m, that is if:

$$\sum_{i=1}^{m} \tilde{A}_i v^{m+1} \geq v^m \Rightarrow (1 - \tilde{A}_{m+1})\Delta v \geq \tilde{A}_{m+1} v^m.$$

This equation defines a minimal incremental value Δv that a member should bring to the community to increase the total benefits for the m existing members.

So, even if a community of size $m+1$ increases the welfare, some members may prefer to have a community of a lower size as they may then have a larger share of the surplus. Indeed, Abada et al. (2020b) show that communities are intrinsically unstable, mainly if they apply simple sharing rules. They recommend sharing value inside the community according to the members' contribution to value and this can be done using sharing rule based on the Shapley value. Indeed, if $B_{m+1} \leq \Delta v$, existing members are not worse off when a new member joins the community.

The question is to know if and how communities can restrict membership if they want to. To answer this question, one needs to know the rules governing the organization of the community and its objective, which is beyond the scope of this paper. Without entering into those considerations, the community can use its prices and the sharing rule to limit participation. Indeed, suppose that the sharing rule is pro rata consumption (or consumption synchronized with production), then, by choosing a sufficiently high membership fee $f > 0$ and a corresponding low electricity price p^s on the zero-profit locus, the community will limit the participation to the members with a sufficiently high consumption. Potential members with a low consumption will not find profitable to pay the fee. Hence, prices and sharing rules can be used to limit participation, even in a system of open participation.

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the members by choosing to sell the electricity just below the retail price $p_s = p_m - \epsilon$ and members do not pay a membership fee $f = 0$. In this case, $B_i = 0$, for all $i \in M$, and all the value created will be profit: $\pi = v$. Again, under full internalization as $v = \Delta C(k)$, a profit maximizing community will choose the first best investment level k^*.

7.5. Rebound effect

Within the community, the local electricity production is a common good that members have access to at a discounted price compared to the market price. For that reason, they may free ride to increase their electricity consumption and the literature has provided evidences of a solar rebound by individual prosumers.[15] They may also displace their load to better synchronize their consumption with the community's production and benefit from lower prices.

Suppose that a member i increases its consumption when the community produces. There are two possible cases, with different consequences. The first case corresponds to a situation where there is still some community production available for internal consumption, *i.e* the extra consumption takes place when the community exports part of its production. In those circumstances, an extra consumption by i leads to an increase in the community total self-consumption $h(k)$ and a corresponding decrease in exports. And, overall, the total value created by the community increases.

In the second case, the consumption increase occurs when all the energy produced is already consumed by the members. Therefore, the extra consumption does not increase the community's self-consumption and it has no impact on its total value. However, as the community's production is a scarce resource and it is already insufficient at that time to cover all the needs of the members, the redistribution of value inside the community will be affected. Depending on the sharing rule, member i may capture a larger fraction of the value, implying that the other members will be left with a smaller fraction.

To encourage the first behavior and deter the second, the community may develop technical solutions to inform its members when it has a production surplus, using an phone application for instance. This approach may leverage social scrutiny of energy consumption to encourage the right behaviors, which have been shown to be effective in the energy context and are likely even more effective in a small, localized, community like the one we consider here.[16] It may also design its internal sharing rule $\boldsymbol{\alpha}$ in such a way that additional consumption does not pay off when there is no production surplus. Finally, the community should anticipate in its investment decision, to the extent that it is possible, the behavioral changes of its member.

8. When prices do not reflect costs

Our efficiency results were based on the assumptions of a cost-reflective grid tariff and a competitive retail market with carbon internalization. In this section, we relax these three assumptions in turn, and show that all RECs are no longer efficient.

8.1. Non coasian grid tariffs

We now discuss the crucial role of grid tariffs in maintaining the efficiency of RECs. The network tariff is a quadruple $(\rho^m, \rho^x, \rho^s, \psi)$ that must satisfy the budget balance constraint for the grid Eq. (2).

If we want that the tariff guarantees that only welfare improving communities are created, one need that the threshold value for the collective self-consumption defined in Eq. (13) coincides with the value in Lemma 2. If we consider a competitive environment with full carbon internalization, it is the case if:

$$\frac{z + \theta^x - (c + \delta + \theta^m)}{\theta^x - \theta^s} = \frac{z + \rho^x - (c + \delta + \rho^m)}{\rho^x - \rho^s}. \tag{19}$$

As the tariff is a 4-uple and there are two equations to be satisfied, *i.e* (2) and (19), many tariffs satisfy these two conditions. In other words, the first best can be achieved with possibly many non-Coasian tariffs.

One concern is that the community can exert a negative externality on non-members. We may add in addition, the grid tariff satisfies the principle of neutrality to non-members, stated in Eq. (3).[17] This tariff can be generically expressed as

$$\rho^m = \theta^m + \eta \quad \text{and} \quad \psi = F - \frac{\eta Q}{n}. \tag{20}$$

In this expression, η is a volumetric surcharge and η could be positive, negative or nil, implying $\psi < F$, $\psi > F$ or $\psi = F$.

The community has no impact on the non-members, if the tariff ρ^m and ψ satisfy Eq. (20) for η. Adding these constraints, the results of Proposition 1 can be extended to:

Proposition 3. *In a competitive environment with carbon internalization, the grid tariffs satisfying*

$$\rho^m = \theta^m + \eta, \rho^x = \theta^x + \eta, \rho^s = \theta^s + \eta, \psi = F - \frac{\eta Q}{n}$$

are such that (i) only energy communities that increase the welfare are feasible (ii) the grid budget is balanced and (iii) communities have no impact on the non-members.

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[15] See for instance Qiu et al. (2019), Boccard and Gautier (2021), Beppler et al. (2023).

[16] See for example Luzzati et al. (2024).

[17] If the community decreases the overall grid cost, some of the cost savings could be passed through non-members. In this case, the community should have no *negative* impact on the non-members. If energy communities reduce the need for additional grid investments, this could result in lowered operational and maintenance costs, benefiting the wider grid user base

Proposition 3 shows that as long as grid tariffs are cost-reflective, they achieve the first best and they have no impact on those who are not members of the community. Variable tariffs can be set above (or below) the marginal cost but as long as the surcharge is the same for all types of exchanges and unchanged after the emergence of a community, the properties of Proposition 3 are preserved.

The design of an appropriate grid tariff for collective self-consumption is a crucial factor for the efficiency and viability of energy communities and is currently a concern for many regulators. Frieden et al. (2021) provided a detailed overview of the various regulations that have been introduced in Europe. Some countries, like Poland, have removed all the volumetric tariff for collective self-consumption. But these regulations may shift the burden of policy costs to non-community members and potentially create a snowball effect (Abada et al., 2020a). Others have differentiated the tariffs depending on the geographical scope of the REC. For example, in the Brussels region, there are four categories of exchanges, each with a different tariff proportional to the geographical scope of the community: exchanges within the same building, within the same low voltage substation, within the same high voltage substation, and between different high voltage substations.

8.2. Non-competitive markets

Consider the case of an imperfectly competitive retail market (along with Coasian tariffs and carbon internalization). Suppose that retailers realize a retail margin[18] $\mu > 0$ such that $p^m = c + \delta + \theta^m + \mu$ while p^x is unchanged at $p^x = c + \delta + \theta^m - \theta^x$. In this case, Eq. (13) no longer coincides with the welfare improvement condition and it is possible to find communities that decrease welfare but that manage to profitably reach the threshold value in Eq. (13). Indeed, now a community can be profitably formed if

$$\varphi(k) \geq \frac{z + \theta^x - (c + \delta + \theta^m)}{\mu + \theta^x - \theta^s}. \tag{21}$$

But we have

$$\frac{z + \theta^x - (c + \delta + \theta^m)}{\mu + \theta^x - \theta^s} = \varphi(\bar{k}) - \frac{\mu}{\theta^x - \theta^s} < \varphi(\bar{k}).$$

So one can state:

Lemma 7. *With non-competitive markets, some energy communities that decrease the welfare are formed and they install too many capacities compared to the first-best.*

With non-competitive markets, retail and export prices reach higher levels than costs and this increases the net value v (see Eq. (12)) that allows the energy community to be feasible. As a result, incentives to install capacity are strengthened. This allows RECs with a lower self-consumption rate than $\varphi(\bar{k})$ to be feasible and to install more capacities not needed to induce social efficiency.

This result highlights that some lack of competition in the retail markets increase the community's value v. As consequences, some communities that do not contribute positively to welfare may form and, communities invest in general in too much production capacity.

8.3. No carbon tax

Next, consider the case of imperfect carbon internalization (along with Coasian tariffs and competitive markets) and to simplify assume that no carbon tax is implemented. As a result energy prices are now such that $p^m = c + \theta^m$ and $p^x = c + \theta^m - \theta^x$ and Eq. (13) again no longer coincides with the welfare improvement condition. Indeed, we now have

$$\varphi(k) \geq \varphi(\bar{k}) + \frac{\delta}{\theta^x - \theta^s} > \varphi(\bar{k}).$$

Lemma 8. *With no carbon tax, some energy communities that are welfare improving are no longer formed and they install less capacities compared to the first-best.*

When there is no carbon tax, energy from CPU is cheaper and the cost differential with DPU increases. As a result, the community value v decreases and communities that increase welfare may not form and those who form invest too little in production capacities.

9. Multiple production technologies

To extend the scope of our main results described in Proposition 1 to 2, we extend our model by considering REC with multiple production technologies. In Appendix C, we use a similar modeling set-up to discuss the possibility to combine production and storage.

We consider two production technologies 1 and 2 (solar and wind). We suppose that it costs $z_j k_j$ for a production of k_j MWh with technology $j = 1, 2$. For a production couple (k_1, k_2) with both technologies, we will denote the associated self-consumption by $h(k_1, k_2)$ and the exports by $k_1 + k_2 - h(k_1, k_2)$. Then $\Phi(k_1, k_2) = \frac{h(k_1,k_2)}{k_1+k_2}$ is the self-consumption rate of the community.

We assume the following.

[18] If we consider that there is also (or instead) a wholesale margin that decrease the import price, the results below are qualitatively the same.

Assumption 5. $h(k_1, k_2)$ with (1) $\frac{\partial h}{\partial k_j} > 0$ for $j = 1, 2$, (2) has negative definite hessian, (3) $\frac{\partial^2 h}{\partial k_1 \partial k_2} < 0$, and (4) $h(k, 0) = h(k)$.

Parts (1) and (2) maintain our assumptions above: self-consumption increases with the capacity installed for each technology and it is concave. Part (3) captures that the two technologies are imperfectly desynchronized and more production by one technology reduces the self-consumption possibilities for the other. The technologies are imperfectly substitutable to provide self-consumption for the community.[19] Part (4) indicates that if only one technology is installed we turn back in our main setting, analyzed since Section 3. Parts (1) and (4) together imply that, for a given production with technology j, adding a second technology $l \neq j$ increases the self-consumption: $h(k_l, k_j) > h(k_j)$.

Our objective is to replicate the above analysis for two production technologies. Denote $K = k_1 + k_2$ and $\mathbf{k} = (k_1, k_2)$. Power flows on the grid write

$$\begin{aligned} V^s &= h(\mathbf{k}) \text{ and } V^x = K - h(\mathbf{k}), \\ V_M^m &= Q_M - h(\mathbf{k}) \text{ and } V_{NM}^m = Q_{NM} - (K - h(\mathbf{k})), \\ V^m &= Q_N - K. \end{aligned}$$

A community producing K increases the welfare if:

$$\theta^m (Q_N - K) + \theta^x (K - h(\mathbf{k})) + \theta^s h(\mathbf{k}) + nF + (c + \delta)(Q_N - K) + z_1 k_1 + z_2 k_2 \leq (c + \delta + \theta^m) Q_N + nF.$$

So the counterpart of (8) is

$$\Delta C(\mathbf{k}) = K \left\{ c + \delta + \theta^m - \left(\sigma_1 z_1 + \sigma_2 z_2 + \theta^x \right) + (\theta^x - \theta^s) \Phi(\mathbf{k}) \right\} \geq 0.$$

where $\sigma_j = \frac{k_j}{K}$ and $\sigma_1 + \sigma_2 = 1$. Let us denote $\tilde{z}(\mathbf{k}) = \sigma_1 z_1 + \sigma_2 z_2$, the average production cost per MWh. A community using two-technologies increases welfare if:

$$\Phi(\mathbf{k}) \geq \frac{\tilde{z}(\mathbf{k}) + \theta^x - (c + \delta + \theta^m)}{\theta^x - \theta^s}. \tag{22}$$

Even if now the right hand side is not independent of $\mathbf{k}$, Eq. (22) is similar to the condition in Lemma 2 defining the first best with a single production technology with now $\tilde{z}(\mathbf{k})$ being the average production cost per MWh. Again a REC increases welfare if $\mathbf{k}$ allows for high levels of self-consumption rates.

In a single technology REC, the first best investment is defined in Lemma 3 as

$$k_j^* : \frac{\partial \Delta C(k_j^*, 0)}{\partial k_j} = 0.$$

In a multiple technology REC, the first best investments are such that[20]

$$(k_1^{**}, k_2^{**}) : \frac{\partial \Delta C(k_1^{**}, k_2^{**})}{\partial k_i} = 0,$$

which writes

$$\frac{\partial h(\mathbf{k})}{\partial k_j} = \frac{z_j + \theta^x - (c + \delta + \theta^m)}{\theta^x - \theta^s}.$$

Lemma 9. *In an interior solution, it is optimal to reduce both investments in each type of technology compared to their counterpart in case of a single technology that is*

$$k_j^{**} < k_j^*.$$

Lemma 9 stems from the substitutability between technologies assumption. Despite lower investments in each technology, the possibility of combining the technologies creates additional value for the REC.

As for the first best, we can reproduce the results of Proposition 1 for the multiple technology case and show that the condition for $\Delta C(\mathbf{k}) > 0$ is identical to $\pi \geq 0$ and $v \geq 0$. In other words, the results of Proposition 1 apply. As shown in our main analysis, the value of REC is a key variable to assess if the above first best capacities can be decentralized by efficient communities. Here, the REC feasibility condition writes:

$$v(\mathbf{k}) = (p^m - \rho^s - p^x) h(\mathbf{k}) + \left(p^x - z_1 \right) k_1 + \left(p^x - z_2 \right) k_2 \geq 0.$$

where $v(\mathbf{k})$ is now the value of REC with two technologies. Each member benefits have been shown to be based on this REC value, *i.e* $B_i = A_i v(\mathbf{k})$, so REC installed capacities (k_1, k_2) are those which solve the problem $\max_{\mathbf{k}} v(\mathbf{k})$. Optimality conditions are:

$$(p^m - \rho^s - p^x) \frac{\partial h(\mathbf{k})}{\partial k_1} = z_1 - p^x,$$

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[19] For an industrial site in Ireland, Sgobba and Meskell (2019) show that solar and wind productions are generally decoupled.

[20] If a production cost is z_j is too high one can have a corner solution with $k_j = 0$. Formally, the condition for a corner solution is $\frac{\partial h(0, k_l^{**})}{\partial k_j} < \frac{z_j + \theta^x - (c + \delta + \theta^m)}{\theta^x - \theta^s}$. In this case, we turn back to our main single technology setting.

$$(p^m - \rho^s - p^x)\frac{\partial h(\mathbf{k})}{\partial k_2} = z_2 - p^x.$$

When full internalization conditions hold, installed capacities are optimal. Again, the organization of the community creates incentives to implement this outcome.

10. Conclusion and policy implications

Renewable energy communities have received a large amount of attention from policymakers in the political world and the regulatory arena. In this work, we first show that, to be beneficial for the energy system as a whole, they need to promote a sufficient amount of electricity consumed close to the place of production. Second, we show that communities lowering the costs of the energy system can emerge in a decentralized way but only if the price of electricity reflects its true cost and this is true in general, *i.e* irrespective of the internal organization of the community or its objective. Finally, we have shown that there exists a subset of welfare-improving tariffs such that the non-members of the communities are not made worse off.

For the political world, our key conclusion is that, yes, renewable energy communities can be beneficial for the energy system. This community-based solution can boost investments in renewable energy sources and help tackle climate change. However, without adequately designed competition and environmental policies leading to the 'right' price of energy, we might see the emergence of welfare-decreasing renewable energy communities. Stand-alone policies promoting only renewable energy communities are unlikely to lead to a successful energy transition. At the European level, the various initiatives promoting community-based solutions in the energy sector like the ones detailed in the revised Renewable Energy Directive (European Parliament & Council of the European Union, 2018) are very welcome but they should be paired with more ambitious carbon and competition policies. Additionally, other legislations supporting energy communities should follow the European example and explicitly consider the benefits of decentralized solution when investments are located close to the point of consumption, as this can lower the overall cost of the energy system by reducing transmission losses and fostering more efficient local supply chains.

In the energy regulatory arena, it is essential to remember that one of the key advantages of renewable energy communities is their ability to boost the renewable investments and their public acceptance. Up to now, large renewable investments have mostly benefited profit-seeking firms and created external negative effects for the local communities in the vicinity of the installations in the form of noise or visual pollution. Smaller-size investments done by individual citizens have enjoyed generous support paid by the public finance system or cross-subsidies financed by non-prosumers via preferential metering systems and relatively low fixed connection charges. Large take-up rates have led to lower public acceptance and tensions around the expansion of renewables. Community-based solutions can circumvent these problems. They can lead to large-scale investment in renewables and share the benefits among the local community, solving the above-mentioned problems.

Our analysis advises caution when designing REC-specific tariffs. Tariffs that are too favorable for members of renewable energy communities can be at the expense of non-members. This is for example the case if the power self-consumed by the community members is free of network charges while it leads to distribution costs for the grid operator. While such regulations would boost the creation of REC, it is important to keep in mind that it could lead to an unfair situation for non-members compared with members, damaging further the acceptance of renewables. Hence, if it leads to a too large boom in investments by renewable energy communities, this kind of tariff design will not be future-proof. Fixing favorable tariffs for local energy flows largely depends on the impact on grid costs of collective self-consumption relative to injection on the low voltage grid. At this stage, more research needs to be done on this issue. This is a critical empirical question that future works should focus on to further refine our regulatory recommendation.

One key topic has yet to be covered in this work and is also one of its key limitations. It is inclusiveness. Renewables are a long-lived asset and they require a significant up-front investment. Renters or low-income households might feel set aside by these communities. Even if, as discussed in Section 6, a low entry ticket might be compensated by a higher price set by the community for the self-consumed energy, the possibility to engage in a community is likely to remain heterogeneous and closely related to the financial situation of potential participants. Renewable energy communities might enhance further distributional concerns and additional complementary policies targeting this problem are needed. We hope that future works will tackle this issue.

CRediT authorship contribution statement

Axel Gautier: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Julien Jacqmin:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Jean-Christophe Poudou:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that there are no competing interests.

Appendix A. Proofs

Proof of Lemma 1. By concavity of h we have for $(y,k) \geq 0$:

$$h(x) \leq h'(k)(y-k) + h(k).$$

Taking $y = 0$, leads for all $k \geq 0$

$$h(0) = 0 \leq -h'(k)k + h(k) \Rightarrow \varphi(k) = \frac{h(k)}{k} \geq h'(k).$$

Then computing φ' implies

$$\varphi' = \frac{h'k - h}{k^2} = \frac{1}{k}\left(h' - \varphi\right) \leq 0.$$

The second derivative of φ is equal to:

$$\varphi'' = \frac{k^3 h'' - 2k(h'k - h)}{k^4} = \frac{kh'' - 2(h' - \varphi)}{k^2}.$$

φ is a convex function if $-kh'' < 2(\varphi - h')$.

Proof of Lemma 2. Straightforwardly from (8). By Assumptions 3 and 4, the ratio is necessarily between 0 and 1.

Proof of Lemma 3. Minimizing the total cost $C_d + C_g$ wrt k leads to the (sufficient from Lemma 1) first order condition:

$$h'(k) = \frac{z + \theta^x - (c + \delta + \theta^m)}{\theta^x - \theta^s}.$$

The right hand side of this equation is strictly smaller than 1 by Assumption 4.

In Lemma 2, we identify $\varphi(\bar{k})$ and we can write $h'(k) = \varphi(\bar{k})$. Consequently,

$$\varphi'(k^*) = \frac{1}{k^*}\left(\varphi(\bar{k}) - \varphi(k^*)\right) \leq 0.$$

Implying $k^* \leq \bar{k}$.

Proof of Proposition 1. Using (14) and (15) in (13), implies $\varphi(k) \geq \varphi(\bar{k})$ where $\bar{k}$ is defined in Lemma 2. Hence whenever $k \leq \bar{k}$ the result holds.

Proof of Lemma 4. Immediate as the locus defined in Eq. (16) is linear.

Proof of Lemma 5. Using the definition of v in Eq. (12), we can write

$$\underline{f} = -\frac{v}{m},\ \overline{f} = \frac{m\underline{\alpha}}{1 - m\underline{\alpha}}\frac{v}{m},\ \underline{p}^s = p^m - \frac{1}{1 - m\underline{\alpha}}\frac{v}{h(k)}. \tag{23}$$

For any $x \in [0,1]$, the benefit B_i can be written as

$$B_i = p^m - (xp^m + (1-x)\underline{p}^s)\alpha_i h(k) - (x\underline{f} + (1-x)\overline{f}). \tag{24}$$

Plugging the values defined in Eq. (23), we have

$$B_i = (1-x)\frac{\alpha_i}{1 - m\underline{\alpha}}v + x\frac{v}{m} - (1-x)\frac{m\underline{\alpha}}{1 - m\underline{\alpha}}\frac{v}{m}. \tag{25}$$

Simplifying, we have

$$B_i = v\left(\frac{(1-x)m\alpha_i + x(1 - m\underline{\alpha}) - (1-x)m\underline{\alpha}}{m(1 - m\underline{\alpha})}\right), \tag{26}$$

which after simplifications gives the expression in the lemma.

Proof of Proposition 2. From Lemma 5, each member i has an individual benefit collinear to v and under full internalization, as $v = \Delta C(k)$, maximizing B_i with respect to k gives k^* for all i. There is unanimity in the choice of k^*.

Proof of Lemma 6. From the definition of $A_i(x)$ in Lemma 5, $A_i(x)$ is increasing in x if $\alpha_i > \frac{1}{m}$ and decreasing if $\alpha_i < \frac{1}{m}$.

Proof of Proposition 3. Plugging (20) in the optimality condition (19) and solving for ρ^s, we have:

$$\rho^s = (\rho^x - (\eta + \theta^x)) \frac{z + \theta^s - (c + \delta + \theta^m)}{z + \theta^x - (c + \delta + \theta^m)} + \eta + \theta^s.$$

Using (20) and this value for ρ^s in the budget balance condition (2) and rearranging the terms, we have:

$$(\rho^x - (\eta + \theta^x)) \left(k + \frac{(\theta^s - \theta^x)}{z + \theta^x - (c + \delta + \theta^m)} h(k) \right) = 0.$$

The last equation gives the unique solution $\rho^x = \theta^x + \eta$ which, plugged in the first equation above, leads to $\rho^s = \theta^s + \eta$.

Proof of Lemma 7. The first part is given by combining the feasibility condition for REC (13) and (21) . Now

$$\varphi(k) \geq \varphi(\bar{k}) - \frac{\mu}{\theta^x - \theta^s} = \varphi(k_\mu).$$

where $\varphi(k_\mu) < \varphi(\bar{k})$, then of RECs such that $k \leq k_\mu$ are formed were $k_\mu > \bar{k}$ from Lemma 1. As a result for $k \in]\bar{k}, k_\mu]$, RECs are feasible but not welfare improving. For the second part, maximizing the net value v for feasible communities defined in (12) and using (21), we have

$$h'(k^*_\mu) = \varphi(\bar{k}) - \frac{\mu}{\theta^x - \theta^s} < \varphi(\bar{k}) = h'(k^*).$$

As h is concave then h' decreases and we have $k^*_\mu > k^*$.

Proof of Lemma 8. Using similar arguments as in Proof of Lemma 7 but in a reverse way, letting $\mu = -\delta$.

Proof of Lemma 9. Due to substitutability between technologies, *i.e* $\frac{\partial^2 h}{\partial k_i \partial k_j} < 0$, then

$$\frac{\partial h\left(k_i, k_j\right)}{\partial k_i} < \frac{\partial h\left(k_i, 0\right)}{\partial k_i} = h'(k_i).$$

As a result by concavity of h, necessarily $\frac{\partial h(k_i, k_j)}{\partial k_i}$ decreases with k_i so this yields the result.

Appendix B. Additional information on self-consumption

B.1. Construction of the self-consumption function

In this appendix, we explain how we can construct the self-consumption level from the meter readings at any time $t \in \mathbb{T} = [0, T]$.
The DPU has a capacity factor $\beta(t)$ and actually produces $k(t) = \beta(t)\tilde{k}$ MWh at a given time t. The cumulative of capacity factors is $\beta = \int_0^T \beta(t)dt$ and the total production (in MWh) of the DPU is $k = \beta\tilde{k} = \int_0^T \beta(t)\tilde{k}dt$.
The consumption of the community members $i \in M$ at time t is denoted by $q_i(t)$ and the aggregated consumption over the T periods, used in the main model, is $q_i = \int_0^T q_i(t)dt$. We denote by $Q_M(t) = \sum_{i\in M} q_i(t)$, the total consumption of the community members at period t.
At any period $t \in T$, either $Q_M(t) \leq k(t)$ or $Q_M(t) > k(t)$. In the first case, the production of the DPU at time t is too large compared to the members' consumption. Therefore, all the community's consumption is covered by the DPU's production and $h(t) = Q_M(t)$. The production surplus $k(t) - Q_M(t) \geq 0$ is exported to the grid and sold to the retailers. In the second case, the local production is insufficient to cover the community's consumption and $h(t) = k(t)$. The community's self-consumption at time t is defined as $h(t) = \min[Q_M(t), k(t)]$ and its aggregate level is an explicit function of k, and computed as:

$$h(k) = \int_0^T \min\left\{Q_M(t), k(t)\right\} dt = \int_0^T \min\left\{Q_M(t), \frac{\beta(t)}{\beta} k\right\} dt.$$

B.2. Empirical support to Assumption 1

To illustrate Assumption 1 and Lemma 1 that is directly derived from, we use data to compute the self-consumption of a fictive energy community as a function of its solar production k. We consider a community that has a yearly consumption of 100 MWh. The consumption profile of the community is represented by a synthetic load profile (SLP) published by Synegrid[21] for Belgium for the year 2022. The community produces its energy with solar panels and we consider different production capacity from 10 to 300 kWp. To convert PV capacity in production, we use a synthetic production profile (SPP) for Belgium from the same source. Production and consumption are defined per $\frac{1}{4}$h. Table 1 reports the production, self-consumption and self-consumption rate for different PV capacities. Figs. 3 and 4 illustrate Assumption 1 and Lemma 1 respectively.

[21] https://www.synergrid.be/fr/centre-de-documentation/statistiques-et-donnees/profils-slp-spp-rlp last accessed on July 17, 2023.

Table 1
Production and self-consumption of an energy community.

Installed capacity (kWc)	Production (MWh)	Self-consumption (MWh)	Self-consumption rate
10	10.41	10.41	100.00%
20	20.83	20.53	98.58%
30	31.24	27.04	86.55%
40	41.65	30.91	74.22%
50	52.07	33.57	64.48%
60	62.48	35.55	56.89%
70	72.89	37.09	50.89%
80	83.31	38.35	46.03%
90	93.72	39.39	42.03%
100	104.13	40.27	38.67%
200	208.26	45.05	21.63%
300	312.40	46.98	15.04%

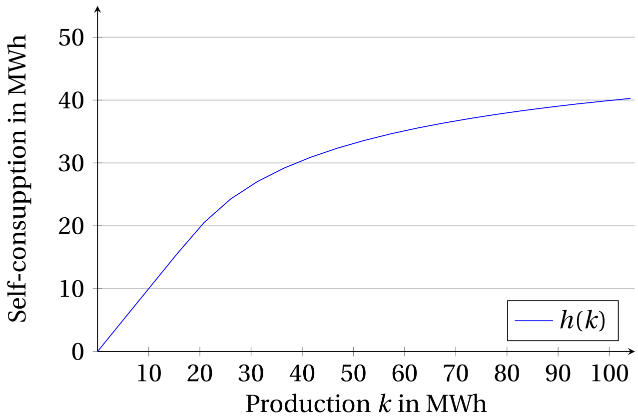

Fig. 3. Self-consumption $h(k)$.

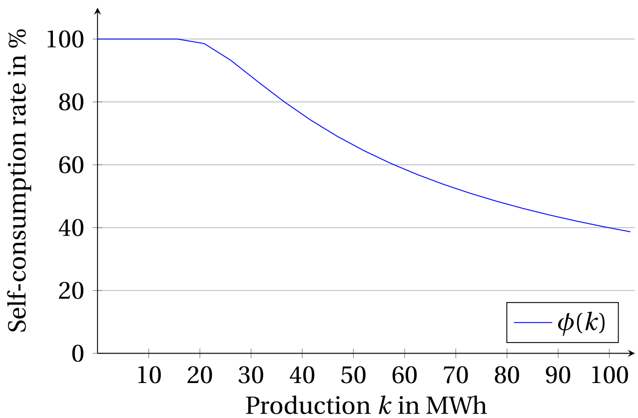

Fig. 4. Self-consumption rate $\phi(k)$.

Appendix C. Production and storage

Usually, we imagine that REC will be able to complement their DPU investments by installing devices that can produce ancillary services they control. A common device that is assumed to create flexibility within the REC is storage. Various studies have pointed out that this complementarity between storage and PV installations is possible via home batteries but also via the batteries of electric vehicles (see for example Kempton and Tomic (2005) or more recently Hoarau and Perez (2018) and Zerrahn et al. (2018)).

In this extension, we use a modeling framework for storage similar to the multiple production technology developed in Section 9 and we show that production and storage are complementary. Our modeling is restrictive in the sense that storage is *only* used to transform exports in collective self-consumption. Indeed, instead of re-injecting in the grid the power produced but not self-consumed, a battery can store a part of this energy flow to be available for "future" self-consumption. In our model, we do not integrate the possibility to use the battery to do arbitrage. With a battery, the community can arbitrate, first, between self-consumption at the current period and self-consumption at a later period, with possible redistributive effects inside the community and, second, between storage, that is future self-consumption and export.[22] To integrate these dimensions in our model, we need to be more explicit on the underlying dynamic and we leave this important dimension for future research.

Suppose that the community can invest in a battery with capacity s at a cost ξs. The battery will increase the collective self-consumption from $h(k)$ to $h(k,s) \geq h(k)$ and $\varphi(k,s) = \frac{h(k,s)}{k}$ is the corresponding self-consumption rate with storage.

Again, we impose some restrictions on the self-consumption function to fulfill realistic stylized facts.

Assumption 6. $h(k,s)$ with (1) $\frac{\partial h}{\partial k} > 0$ and $\frac{\partial h}{\partial s} > 0$, (2) has negative definite hessian (3), $\frac{\partial^2 h}{\partial k \partial s} > 0$, and (4) $h(k,0) = h(k)$, $h(0,s) = 0$ and $h(k,s) \leq k$.

The model is quite similar to the previous case with two technologies, but now part (3) implies that more storage capacities increase the self-consumption potential of the DPU. In some sense, both DPU and storage are complements from the point of view of self-consumption in the REC. For example, Roberts et al. (2019) found in their simulations that a shared battery in an apartment building can increase PV self-consumption by close to 20%, and this may even double according to Zakeri et al. (2021), for home batteries.

Mimicking the developments above, it is then possible to see quite directly that a community producing k and installing a battery s increases the welfare if

$$\Delta C(k,s) = (c + \delta + \theta^m - (z + \theta^x))\,k + (\theta^x - \theta^s)\,h(k,s) - \xi s \geq 0.$$

Compared to the no storage case (see Lemma 3) the optimality condition is unchanged for the DPU capacity and the optimal storage capacity entails

$$\frac{\partial \Delta C(k,s)}{\partial s} = (\theta^s - \theta^x)\,\frac{\partial h(k,s)}{\partial s} + \xi = 0 \Rightarrow \frac{\partial h(k^{**},s^*)}{\partial s} = \frac{\xi}{\theta^x - \theta^s} > 0.$$

Due to complementarities between DPU and storage, *i.e* $\frac{\partial^2 h}{\partial k \partial s} > 0$, then

$$\frac{\partial h(k,s)}{\partial k} > \frac{\partial h(k,0)}{\partial k} = h'(k).$$

As a result by concavity of h, necessarily $\frac{\partial h(k,s)}{\partial k}$ decreases with k and then it is optimal to increase the DPU investment compared to the no-storage situation that is

$$k^{**} > k^*.$$

The presence of storage capacity in a community enhances their economic efficiency. First, it is socially optimal to invest jointly in storage and production capacities. Second, storage increases the renewable capacity installed by the community.

With storage, the REC feasibility condition writes

$$v = (p^m - \rho^s - p^x)h(k,s) + (p^x - z)\,k - \xi s \geq 0.$$

where v is now the value of REC with storage. Same arguments then with two technologies applies and REC installed capacities (k,s) are those which solve the problem $\max_{k,s} v$. Optimality conditions are:

$$(p^m - \rho^s - p^x)\frac{\partial h(k,s)}{\partial k} = z - p^x,$$

$$(p^m - \rho^s - p^x)\frac{\partial h(k,s)}{\partial s} = \xi.$$

When full internalization conditions hold, the community installs DPU and storage capacities that are optimal.

Appendix D. Nomenclature of variables

In Table 2, we provide a nomenclature of variables used in our model.

Data availability

No data was used for the research described in the article.

[22] And these possibilities of arbitrage would be further increased with time-dependent prices.

Table 2
Nomenclature of variables.

Index	Description
A_i	Individual share of total benefits for member i
B_i and B	Member i and total benefit
c	CPU energy production unit cost
C_d and C_g	Total distribution cost and generation cost
f	Membership fee
F	Fixed grid cost per user
h	Collective self-consumption in the REC
k and $\tilde{k}$	Production of the DPU (in MWh) and capacity (in MW)
K	Total DPU production (when multiple technologies)
n and N	Number and set of consumers
m and M	Number and subset of members of the REC
p^j	Energy prices from flow/usage j
q_i and Q	Electric consumption for an agent i and total amount
Q_M and Q_{NM}	Total electric consumption of the REC members and non members
s	Battery capacity
T	Number of time periods (time horizon)
v	Total value created by the community
V^j	Volumes of power exchanges from flow/usage j
x	Weight in $[0, 1]$
z and $\tilde{z}$	Unit costs of installation of DPU (per MWh and per MW)
α_i and $\underline{\alpha}$	Share of h allocated to member i and their minimum value
β	Average load factor of a DPU
δ	Unit environmental externality per MWh
ΔC	Social cost saving
θ^j	Variable grid costs of power distribution from usage j
μ	Non competitive retail margin
π	Profit of the REC
ρ^j	Grid variable fee from usage j
η	Volumetric surcharge
φ	Collective self-consumption rate
σ_l	Production share of technology l (when multiple technologies)
τ	Carbon unit tax
ξ	Unit cost of installation of battery
ψ	Grid fixed fee per user

References

Abada, I., Ehrenmann, A., Lambin, X., 2020a. Unintended consequences: The snowball effect of energy communities. Energy Policy 143, 1–14.
Abada, I., Ehrenmann, A., Lambin, X., 2020b. On the viability of energy communities. Energy J. 41 (1), 113–150.
Bauwens, T., Devine-Wright, P., 2018. Positive energies? An empirical study of community energy participation and attitudes to renewable energy. Energy Policy 118, 612–625.
Beppler, R., Matisoff, D., Olivier, M., 2023. Electricity consumption changes following solar adoption: Testing for a solar rebound. Econ. Inq. 61, 58–81.
Boccard, N., Gautier, A., 2021. Solar Rebound: The unintended consequences of subsidies. Energy Econ. 100, 105334.
Brown, D.P., Sappington, D.E., 2017. Designing compensation for distributed solar generation: Is net metering ever optimal? Energy J. 38 (3).
Cambini, C., Soroush, G., 2019. Designing grid tariffs in the presence of distributed generation. Util. Policy 61, 100979.
Cortade, T., Poudou, J.C., 2022. Peer-to-peer energy platforms: Incentives for prosuming. Energy Econ. 109, 105924.
De Villena, M., Aittahar, S., Mathieu, S., Boukas, I., Vermeulen, E., Ernst, D., 2022. Financial optimization of renewable energy communities through optimal allocation of locally generated electricity. IEEE Access 10, 77571–77586.
Dudka, A., Moratal, N., Bauwens, T., 2023. A typology of community-based energy citizenship: An analysis of the ownership structure and institutional logics of 164 energy communities in France. Energy Policy 178, 113588.
European Parliament & Council of the European Union, 2018. EU directive 2018/2001 on the promotion of the use of energy from renewable sources. Off. J. Eur. Union.
Fabra, N., Reguant, M., 2024. The energy transition: A balancing act. Resour. Energy Econ. 76, 101408.
Felice, A., Rakocevic, L., Peeters, L., Messagie, M., Coosemans, T., Ramirez Camargo, L., 2022. Renewable energy communities: Do they have a business case in Flanders? Appl. Energy 322, 119419.
Frieden, D., Tuerk, A., Antunes, A.R., Athanasios, V., Chronis, A.G., dH́erbemont, S., Gubina, A.F., 2021. Are we on the right track? Collective self-consumption and energy communities in the European union. Sustainability 13 (22), 12494.
Gautier, A., Jacqmin, J., Poudou, J.C., 2018. The prosumers and the grid. J. Regul. Econ. 53 (1), 100–126.
Gautier, A., Jacqmin, J., Poudou, J.C., 2021. Optimal grid tariffs with heterogeneous prosumers. Util. Policy 68, 101140.
Gonzalez, F.F., Sauma, E., van der Weijde, A.H., 2022. Community energy projects in the context of generation and transmission expansion planning. Energy Econ. 108, 105859.
Hanke, F., Guyet, R., Feenstra, M., 2021. Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases. Energy Res. Soc. Sci. 80, 102244.
Hanke, F., Lowitzsch, J., 2020. Empowering vulnerable consumers to join renewable energy communities - Towards an inclusive design of the Clean Energy Package. Energies 13 (1615).
Hoarau, Q., Perez, Y., 2018. Interactions between electric mobility and photovoltaic generation: A review. Renew. Sustain. Energy Rev. 94, 510–522.
Iazzolino, G., Sorrentino, N., Menniti, D., Pinnarelli, A., De Carolis, M., Mendicino, L., 2022. Energy communities and key features emerged from business models review. Energy Policy 165, 112929.

Ines, C., Guilherme, P.L., Esther, M.G., Swantje, G., Stephen, H., Lars, H., 2020. Regulatory challenges and opportunities for collective renewable energy prosumers in the EU. Energy Policy 138, 111212.
IPCC, 2022. Climate change 2022: Mitigation of climate change. In: Contribution of Working Group III To the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.
Kempton, W., Tomic, J., 2005. Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy. J. Power Sources 144 (1), 280–294.
Lazzeroni, P., Mariuzzo, I., Quercio, M., Repetto, M., 2021. Economic, energy and environmental analysis of PV with battery storage for Italian households. Electronics 10 (146).
Loebbe, S., Sioshansi, F., Robinson, D., 2022. Energy Communities: Customer-Centered, Market-Driven, Welfare-Enhancing? Academic Press.
Luzzati, T., Mura, E., Pellegrini, L., Raugi, M., Salvati, N., Schito, E., Scipioni, S., Testi, D., Zerbino, P., 2024. Are energy community members more flexible than individual prosumers? Evidence from a serious game. J. Clean. Prod. 444, 141114.
Norbu, S., Couraud, B., Robu, V., Andoni, M., Flynn, D., 2021. Modelling the redistribution of benefits from joint investments in community energy projects. Appl. Energy 287, 116575.
Pierre, B., Mutabazi, F., Garcet, J., Doclo, M., Jahn, R., Crunelle, C., 2022. Can renewable energy communities increase the use of the flexibility of electric vehicles? In: CIRED Porto Workshop 2022: E-Mobility and Power Distribution Systems, vol. 2022, pp. 528–532.
Qiu, Y., Kahn, M.E., B., Xing, 2019. Quantifying the rebound effects of residential solar panel adoption. J. Environ. Econ. Manag. 96, 310–341.
Reis, I.F.G., Gonçalves, I., Lopes, M.A.R., Henggeler Antunes, C., 2021. Business models for energy communities: A review of key issues and trends. Renew. Sustain. Energy Rev. 144, 111013.
Roberts, M.B., Bruce, A., MacGill, I., 2019. Impact of shared battery energy storage systems on photovoltaic self-consumption and electricity bills in apartment buildings. Appl. Energy 245, 78–95.
Rossetto, N., Verde, S.F., Bauwens, T., 2022. A taxonomy of energy communities in liberalized energy systems. In: Lobbe, S., Sioshansi, F., Robinson, D. (Eds.), Energy Communities. Academic Press, pp. 3–23.
Schittekatte, T., Meeus, L., 2020. Least-cost distribution network tariff design in theory and practice. Energy J. 41 (5).
Sgobba, A., Meskell, C., 2019. On-site renewable electricity production and self consumption for manufacturing industry in Ireland: Sensitivity to techno-economic conditions. J. Clean. Prod. 207, 894–907.
Shivashankar, S., Mekhilef, S., Mokhlis, H., Karimi, M., 2016. Mitigating methods of power fluctuation of photovoltaic (PV) sources: A review. Renew. Sustain. Energy Rev. 59, 1170–1184.
Zakeri, B., Cross, S., Dodds, P.E., Castagneto Gissey, G., 2021. Policy options for enhancing economic profitability of residential solar photovoltaic with battery energy storage. Appl. Energy 290, 116697.
Zerrahn, A., Schill, W.-P., Kemfert, C., 2018. On the economics of electrical storage for variable renewable energy sources. Eur. Econ. Rev. 108, 259–279.