The energy community and the grid[*]

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Abstract

Renewable energy communities involve various agents who decide to jointly invest in renewable production units and storage. This paper examines how these communities interact with the energy system and can decrease its overall cost. First, we show that a renewable 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 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, we argue that various internal organization of the renewable energy communities are feasible. The internal organization impacts the distribution of benefits among members but not the global efficiency of the community.

Keywords: Energy communities, decentralized production units, energy transition, grid
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1 Introduction

Community-based solutions are a private approach to potentially correct various market failures and to ease energy transition. In the energy sector, compared to decentralized investments from individual consumers into renewable energy sources, energy communities can leverage additional renewable production capacities, closer to the place of consumption, and in places where it is complicated otherwise. Think for instance on the rooftop of an apartment building

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shared by multiple households. More generally, the idea is that citizens, firms and organizations, located in the same neighborhood form a community and invest collectively in renewable production units like wind and solar and in storage facilities. And, the energy that the community produces locally can be shared and collectively self-consumed by the members.[1] The idea is that the community sells the energy self-consumed at a discounted price compared to the commercial retailers, bringing benefits to the members and, under conditions, to the energy system as a whole. Local exchanges inside the community take place on the public grid and, to facilitate energy sharing, an appropriate regulatory framework for collective self-consumption should be designed. This paper adresses these two questions, the efficiency of the community and the appropriate regulatory framework for power exchanges.

In recent years, policy makers have discussed how to best integrate these new initiatives in the renewable energy landscape. According to IPCC (2022), “Energy communities help in increasing public acceptance and mobilise private funding”. In Europe, the Green deal aims to make Europe carbon neutral by 2050 (European Commission (2021)). The intermediary goal is to reach 45% of renewables in the EU energy mix by 2030 as stated by the REPower EU plan of 2022 with policies detailed in the “Clean Energy for all” European package (European Commission (2019)). The general framework ruled by European institutions calls to “promote this actively with provisions on self-consumption of energy, and local and renewable energy communities”.[2] In the United States, the U.S. Department of Energy (DOE) aims to have 5 millions homes be part of a solar energy community by 2025 (U.S. Department of Energy (2021)). In the Inflation Reduction Act of 2022, solar communities projects can benefit a 10% bonus on the benchmark income tax credit if the community benefits disadvantaged citizens. Elsewhere, renewable energy communities are also attracting the attention of policymakers, leading to various initiatives worldwide, not only in developed countries but also in lesser developed ones like Guatemala, Philippines, Costa Rica or Burkina Faso (IRENA (2020)).

Whether these communities will emerge naturally and be integrated into the energy system by bringing along system-wide benefits remain unclear. In this paper, we model the integration of renewable energy communities in an energy system composed of consumers, energy producers and retailers and a regulated grid network connecting together all the agents. The community invests in production and storage and sells the energy to its members and the surplus to the market. Our model discusses the conditions for a community to be feasible and compares these conditions with those for welfare maximization to identify the circumstances under which the two coincide. Our model also discusses the internal organization of the community to identify

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[1] Energy communities differ from peer-to-peer trading platforms in at least two dimensions. First power exchanges within a community should have a local dimension. Second, the community owns assets, production units and batteries, while on peer-to-peer platforms, assets are owned individually by the participants.

[2] It requires member states to transcribe 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.

the prices prevailing for the exchanges taking place within the community.

Our analysis provides the following takeaways. First, we highlight when renewable energy communities are welfare-improving. The key conditions to be respected relate to a minimum amount of self-consumption inside the community. As the energy produced by the community is consumed at the place of production, it is a cheaper solution than to transport it from a traditional retailer to consumers and this can be beneficial for the energy system as a whole. Second, we show that, if consumers pay the true cost of the centrally produced electricity (that is the retail market is competitive and a carbon tax equal to the value of the emissions it produces is implemented and grid tariffs reflect costs), only renewable energy communities that increase welfare are feasible. Importantly, this result does not depend on how the electricity is priced and shared inside the community. Hence, in this context, decentralized, community-based solutions can be a suitable approach to boost the deployment of renewable energy sources. In addition, we also show that there is a subset of welfare improving grid tariffs that have a non-negative impact on non-members of the community, henceforth limiting distributional issues that could in fine impair the social acceptability of renewable energy communities. However, if the retail market is imperfectly competitive, too much capacities will be installed and this will decrease welfare. If there is no externality-internalizing carbon tax, some welfare improving communities will not emerge and too few capacities will be installed by renewable energy communities. Third, we show that irrespective of how the energy surplus is shared among the community, various entry tickets into the energy community and prices paid for the self-consumed electricity can lead to the creation of the first best community and renewable capacity level. In other words, the efficiency of the community is independent on its internal organization.

Our work is linked to the economic literature looking at the integration of distributed generation of electricity. This literature has focused mainly on the incentives for individuals to invest in distributed generation, mainly solar panels. Brown and Sappington (2017) look at whether a net metering system can optimally connect prosumers to the grid where they import electricity when they do not produce electricity and they export their electricity when their production exceeds their own consumption. They conclude that it is unlikely and that it can create distributional issues between investors and non-investors in distributed generation units. Gautier, Jacqmin and Poudou (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, the synchronization of local production and consumption such as by encouraging the installation of batteries or load shifting. They identify regulatory environments that provide appropriate incentives for individual investments. Gautier, Jacqmin and Poudou (2021) generalize 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. 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.

Taking into consideration the idea that investments in distributed generation units can be made by a community, two papers are more closely related to our work. Abada, Ehrenmann and Lambin (2020a) analyze the conditions under which a grid death spiral can happen with the emergence of energy communities. Assuming that self-consumed energy does not pay for the variable grid component of the bill, new tariffs need to be implemented in order for the grid operator to be able to break even. As these higher tariffs favor the creation of renewable energy communities by its members, tariffs need to be updated upwards to sustain the financing of the grid. The authors argue that this can lead to a snowball effect, especially if the tariffs are computed based on the electricity imported from the grid rather than via a fixed fee. Abada, Ehrenmann and Lambin (2020b) focuses on how the energy surplus is shared among the participants of the community and look whether it can lead to a stable community using the tools of cooperative game theory. They investigate various allocation keys like per capita, pro rata consumption, pro rata peak demand and Shapley value. Their main result is that simple rules generate unstable communities and that it is worth aligning the distribution rule with the contribution to the value of the community as done, for instance, by the Shapley value.

Our paper relates to a recent strand in the literature that focuses on the feasibility of renewable energy communities. Part of this literature focuses on the technical challenges and the solutions to manage them using a techno-economic approach. These challenges relate to the management and billing of energy flows inside the community (De Villena et al. (2022)), the development of algorithms able to improve the redistribution of the benefits created by an investment done by a renewable energy community (Norbu et al. (2021)) or on how the smart charging of electric vehicles can be optimized at the energy community level (Pierre et al. (2022)). Other techno-economic works focus rather on how communities interact with the rest of the energy system. For example, Gonzalez et al. (2022) develop a mathematical program to evaluate the impact of renewable energy communities on the power transmission system. The other important strain of this literature focuses on economic challenges related to renewable energy communities. For example, Reis et al. (2021) or Iazzolino et al. (2022) review the features of different business models for renewable energy communities. Hanke and Lowitzsch (2020) and Hanke et al. (2022) assess to which extent renewable energy communities can help vulnerable consumers and whether they do. All these key issues are also covered in great length in a collective work coordinated by Loebbe, Sioshansi and Robinson (2022).

In Section 2, we present our model. The first best is derived in Section 3. In Section 4, we describe the decentralized outcome and the conditions under which it coincides with the first best. The internal organization of the community is exposed in Section 5. Section 6 discusses what happens when the energy prices do not reflect their costs. Section 7 provides two extensions regarding the investment in different production technologies and in storage. Section 8 concludes. All the proofs are in Appendix A.

2 Model

We consider an energy system where competitive retailers have centralized production units (CPU) and sell electricity to their clients. In this energy system, a group of consumers (in a neighborhood, a business district or within a building) can form a renewable energy community that invests in decentralized production units (DPU) and in storage. The DPU are connected to the low voltage grid and they are green substitutes to the CPU. The community sells its production to its member and the surplus to the retailers. All the power exchanges use the public electricity grid and there are (regulated) grid fees charged for power exchanges.

2.1 Electricity generation

CPU produce electricity at a cost c per MWh. CPU mainly use non-renewable production technology and their production has, in addition, an environmental externality δ per MWh produced. DPU use a renewable energy source (wind or solar). The production technology has a capacity factor β and a DPU with capacity $\tilde{k}$ produces $\beta\tilde{k}$ MWh. The cost per unit of capacity is $\tilde{z}$. We will denote by $k = \beta\tilde{k}$ the production (in MWh) of a DPU with capacity $\tilde{k}$. The cost per MWh can be expressed as $z = \frac{\tilde{z}}{\beta}$ i.e. it costs zk to produce k MWh.

In the baseline model, we consider a single production technology without storage and integrate these two dimensions as an extension.

2.2 Electricity consumption

We consider a population of a set N of n inhabitants. Each inhabitant $i \in N$ has a given consumption profile, with an aggregated consumption denoted by q_i.[3]

There are two categories of inhabitant. A subset M of the population with m members, can form a renewable energy community (REC). The consumption of the REC's members will be covered by the community's production and by the retailers. The remaining $n - m$ inhabitant will be not be part of the community and their consumption will be entirely covered by the retailers.

We will denote by $Q_M = \sum_{i \in M} q_i$, the total aggregate consumption of the community members, by $Q_{NM} = \sum_{i \in N \setminus M} q_i$ the total consumption of the non-members and the total consump-

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[3] With smart meters, the individuals' consumption and the DPU's production are measured in almost continuous time (usually every quarter of hour). In the model, we aggregate consumption over all time steps as only aggregated values are important to determine the REC's profit and the individual benefits. The instantaneous value are only used to determine the self-consumption level by comparing at each time step the community's consumption and production.

tion by $Q = Q_M + Q_{NM}$.

2.3 Power exchanges

All the power exchanges take place on the public electricity grid and the community has no network infrastructure on its own. There are different types of power exchanges represented in Figure 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 we 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 the other consumers outside of the community. We refer to this as an *export* to the grid and we denote the export's volume by V^x. Exports from the community reduces the import of the non community members, and therefore the production of the CPU. Finally, part of the energy produced by the community is consumed by the members. We refer to this as the community's *self-consumption* and we denote the self-consumption volume by V^s.

The community's self consumption depends on, firstly, the synchronization between the production and the consumption profiles, secondly, on the level of production itself and, thirdly, on the capacity to store electricity at the production place. A higher synchronization, a higher production and a higher storage capacity will increase the self-consumption volume. We will denote by $h(k) \geq 0$ the electricity produced by the DPU that is self-consumed by the community's members 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 consumption (by definition), the second part means that self-consumption increases with production but at a decreasing rate. A consequence of this assumption is there is no self-consumption without investment : $h(0) = 0$. 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 *φ is non-increasing in k.*

This result is a direct consequence of concavity of the 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, we provide further empirical evidences to illustrate Assumption 1 and Lemma 1.

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.

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

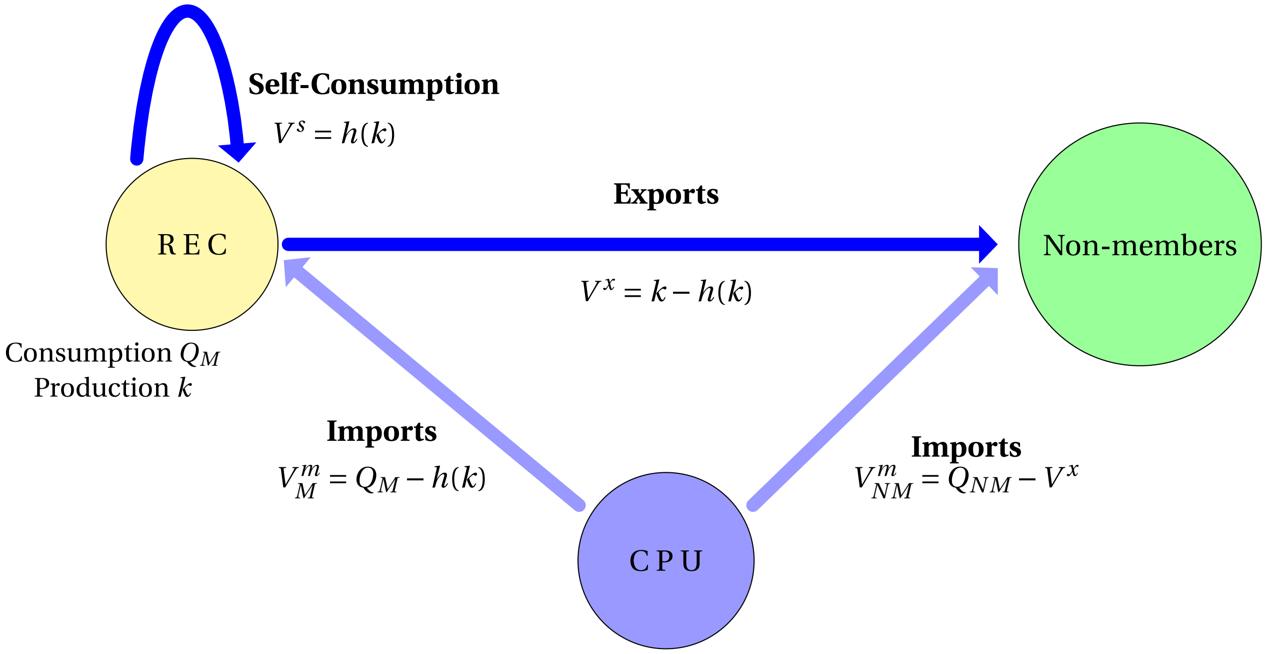

Figure 1: Power Exchanges

2.4 Grid cost

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.[4] The variable cost includes all the current and future network developments that should be undertaken in order to cope with power exchanges, including injections by the DPU.[5]

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[4] In practice, regulators impose to the grid operators the funding of different energy policies like the support to renewables. These costs add in to the infrastructure costs and they are financed by specific surcharges, volumetric or fixed.

[5] In the European context, there are two definitions for what is an energy community. This is detailed in two separate directives: the Internal Electricity Market directive (European Parliament & Council of the European Union (2019)) introduces 'citizens energy communities' and the revised Renewable Energy Directive (European Parlia-

We suppose that the variable cost is specific to each power flow and we 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 potentially generates higher costs for the grid. This is mostly due to the historical design of power systems which was developed as "one-way" from producers to consumers. These costs include additional investments in on-load tap changers, booster transformers or static volt ampere reactive compensator to accommodate the greater variations in voltage (Shivashankar et al. (2016)). Furthermore, local power exchanges reduce power losses.[6]

Consequently, we will assume that:

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

The total distribution cost is equal to

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

The grid charges grid fees to cover the distribution cost C_d and grid fees are usually regulated. There are two types of fee: a fixed fee (ψ) per user and a variable fee per MWh. This variable fee can be specific to each flow and we denote by ρ^m, ρ^x and ρ^s the fee applied for imports, exports and self-consumption.[7]

The grid fees must be such that the grid operator manages to cover its costs:

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

Network tariffs have an impact on community members and non-members. In particular, Abada *et al.* (2020a) show 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 but also the non-community members. And this of course is a concern as communities possibly exert externalities on non-members.

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ment & Council of the European Union (2018)) defines ‘renewable energy communities’. The two differ in part on their geographical scope. Our definition is closer to the latter as participants have to be organized in the proximity of the renewable energy project resulting from the community. In the case of citizen energy communities, it is less obvious that the different power flows lead to varying costs for the grid.

[6] The physical boundaries of what is precisely meant by local for a REC depends on the specific legislation. As discussed by Frieden et al. (2021) for the European context, this definition was fully left to 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 on the same low voltage transformer stations. In other places like Wallonia (Belgium) or Portugal, the definition of what is local is assessed on a case-by-case.

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

To avoid transferring the burden of the grid costs to non-members, we can add an additional constraint in the tariff design to guarantee that the formation of a community has no impact on the bill of citizens outside of it. Indeed, 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).

2.5 Hypothesis

We make the following assumptions on production and grid costs. First, we suppose that the DPU are not efficient substitutes to the CPU to serve non-local consumers. In other words, it is not efficient that energy retailers invest in DPU.

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

Second, 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 assumption implies that the DPU will be preferred to CPU if the self-consumption rate is high enough.

2.6 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. We will take the convention that the grid fees for imports and exports are paid by the retailers. The retailers' profit is equal to:

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

Where τ is the carbon tax set to compensate the CO2 emissions of the CPU.[8]

The first term in Equation (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 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 imply 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 *In a competitive market, the electricity prices are equal to*

$$\begin{aligned} p^m &= c + \tau + \rho^m && (5) \\ p^x &= p^m - \rho^x = c + \tau + \rho^m - \rho^x && (6) \end{aligned}$$

In a market that is not perfectly competitive, retailers will be able to sell electricity at a price above the retail price defined in Equation (5) and/or to buy electricity from the community at a price below the export price defined in Equation (6). In both cases, it leads to a positive profit for the retailers.

3 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:

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

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[8] Note that fixed fees $n\psi$ are collected by retailers but also directly transferred to the grid operator, that is why they do not appear in (4)

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:

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

The first term in Equation (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, 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*

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

This condition means that a REC increases the welfare if the share of electricity produced that is self consumed is large enough. With a decreasing self-consumption rate, the lemma defines an upper bound on the REC production below which the existence of the REC positively contributes to the welfare.

The RHS in the above condition is the ratio between the additional cost of serving consumers with DPU rather than with CPU over the savings generated by self-consumption. It can be interpreted as the percentage of self-consumed electricity that is necessary to offset the additional cost of decentralized production.[9] If the community self-consumption rate is above this ratio, savings from self-consumption more than compensate the additional production costs and it increases 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*

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

Lemma 3 expresses that the welfare maximizing community investment trades-off additional production costs and savings from self-consumption.

4 Feasible energy community

In the sequel, we suppose that m potential members have the opportunity to form an energy community. Member i will participate if he derives a net monetary benefit i.e. if participation to

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[9] By Assumptions 3 and 4, this ratio is necessarily between 0 and 1.

the community decreases his energy bill.[10] We now discuss the feasibility of a community and in the next section how they are organized.

4.1 The community budget constraint

The community will propose to the m potential members to collectively invest in the production of 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.

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 a reduced membership fees or as a reduced energy price. Eventually, the membership fee could be negative and the community can redistribute its profits to the members as dividends.[11]

4.2 The community participation constraint

The community proposes a sharing rule to share the 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* (2020) provide examples and discuss the merits of different sharing rules. In the sequel, 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 $p^m\left(q_i - \alpha_i h(k)\right) + p^s \alpha_i h(k) - f - \psi \geq p^m q_i - \psi$. This also means if 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 $i \in M$:

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

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[10] 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 to social norms related to joining a community.

[11] If the community has no access to capital markets, the membership fee should be large enough to finance the capital cost: $mf \geq zk$.

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

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

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.

4.3 Feasible communities

A community is feasible at two conditions. First, it should create value for its members (Equation 11). Second, the community as a whole should realize a non negative profit $\pi \geq 0$. Combining the two conditions, a community is feasible if its value v is such that:

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

Equation (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 $\boldsymbol{\alpha}$. Equation (12) can be expressed equivalently as:

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

This equation can be interpreted similarly to the condition in Lemma 2 as the ratio between the cost for the community of serving consumers with DPU: the electricity being produced at cost z and sold at price p^x and the benefits generated by self-consumption: electricity is sold at price p^m to members instead of p^x to the grid and the REC pays, in addition a grid cost ρ^s. If the self-consumption rate is larger than this ratio, the community is feasible.

The feasibility condition only depends on the market conditions, the retail and the wholesale prices, and the regulatory environment and the self-consumption rate. It is therefore possible to assess the feasibility of a community based on a single of its characteristic: the community self-consumption rate. If the self-consumption rate is high enough (Equation 13), the community is feasible; otherwise it is not.

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 to encourage 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.

4.4 Non Coasian grid tariffs

The above results are based on assumptions of a Coasian tariff and a competitive environment with carbon internalization. We now discuss the crucial role of grid tariffs to maintain the efficiency of RECs. As we mentioned above, the network tariff is a quadruple $(\rho^m, \rho^x, \rho^s, \psi)$ that must satisfy the budget balance constraint for the grid (Equation 2). The tariff must be such that the community creates value (Equation 13) and only welfare improving communities are created (Lemma 2). If we consider a competitive environment with full carbon internalization, these conditions are equivalent to:

$$\frac{z + \theta^x - (c + \delta + \theta^m)}{\theta^x - \theta^s} = \frac{z + \rho^x - (c + \delta + \rho^m)}{\rho^x - \rho^s} \tag{16}$$

$$(\rho^m - \theta^m)(Q - k) + (\rho^x - \theta^x)(k - h(k)) + (\rho^s - \theta^s)h(k) + n(F - \psi) = 0 \tag{17}$$

As the tariff is a 4-uple and there are two equations to be satisfied, there are many tariffs that 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 requirement that the community has no impact on non-members. If we suppose that, in the absence of a community, the regulator applied a tariff given by the budget balance condition for the grid (Equation 3). This tariff can be generically expressed as

$$\rho^m = \theta^m + \beta\,;\; \psi = F - \frac{\beta Q}{n} \tag{18}$$

In this expression, β is a volumetric surcharge and β 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 equation (18) for β. Adding these constraints, the results of proposition 1 can be extended to:

Proposition 2 *In a competitive environment with carbon internalization, the grid tariffs satisfying*

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

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.

Proposition 2 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 2 are preserved.

This proposition is important as some advocate for a waiver of the grid fee for the self-consumed energy, without other considerations, that is $\rho^s = 0$ in our setting. In this case, our proposition shows that this option implies that at least one condition above is violated. For implementing $\rho^s = 0$, one need $\beta = -\theta^s < 0$ implying lower volumetric fees for all flows and an increased fixed fee $\psi = F + \frac{\theta^s Q}{n} > F$ for all agents. As requested by Article 16(e) of the Internal Electricity Market Directive (European Parliament & Council of the European Union (2019)), tariffs are expected to be cost-reflective. With $\rho^s = 0$, this situation is possible only in very restricted cases. For example, this is can be true if the electricity collectively self-consumed flows only via the private grid connecting community members located in the same apartment building, where cables are the property of the owners of the building. Here, the electricity self-consumed by the community does not need to flow via the public electricity grid at all and $\theta^s = 0$.

The design of an appropriate grid tariff for collective self-consumption is an important element for the efficiency and the viability of energy communities. In practice, the volumetric part of the grid tariff are used to cover, at least partially, the grid's fixed costs and they include, in addition, different volumetric surcharges to finance energy policies like the promotion of renewables. Regulators should decide on the grid tariff and the surcharges that are applicable to collective self-consumption. At this stage (see Frieden et al. (2021) for a detailed overview), very diverse regulations have been introduced and can be discussed in the light of Proposition 2.

In Spain, where energy communities must connect members on the same secondary substation with a maximum distance of 500 meters between the source of production and consumption, there is no grid fee for the collectively self-consumed electricity but all the surcharges should be fully paid. In Poland, volumetric surcharges are removed for collective self-consumption. These regulations are likely to transfer the burden of network an policy costs to non-community members and to create a snowball effect (Abada *et al.* (2020a)), leading ultimately to the emergence of too many RECs.

As the network costs related to local energy exchanges are proportional to the geographical scope of the REC, local energy tariffs differentiated with the physical boundaries should be encouraged. This is for example the case in Portugal where collective self-consumption does not have to pay the grid fees above the grid level of the REC or in Italy where the REC does not pay for the transmission part of the grid tariff. In Brussels (Belgium), the tariff regulation goes even one step further. There are four different tariffs for the local energy exchanges that are linked to the geographical scope of the REC, ranging from zero when members and their installations are located in the same building to the full distribution and transmission tariffs when they are connected via different medium voltage substations.[12]

5 Organization of the community

According to Article 2 (16) of the renewable energy directive (EuropeanParliament & 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". 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. Communities can have different organizational forms in accordance with national laws but need to be "based on open and voluntary participation, autonomous and effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects". Nevertheless, proposition 1 showed that, irrespective of their goals or internal organization, only welfare enhancing communities are feasible. In this section, we go one step further and we identify the set of prices that could be implemented within a community and the preferences of the members over prices and capacities.

5.1 Community prices

For a given production k, we can define using Equation (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:

$$p^s = \rho^s + p^x + \frac{z - p^x}{\varphi(k)} - \frac{m}{h(k)} f \tag{19}$$

It is represented on Figure 2, and it shows a negative relation between the membership fee f and the energy price p^s. If the community is zero-profit, it has to select a point (p^s, f) on this locus such that all participation constraints are satisfied. 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

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[12] Another possibility is to have case-by-case network tariffs prevailing for collective self-consumption depending on REC-specific assessment. One problem with this approach is that it makes it more complicated to promote REC by adding an extra-administrative burden to this kind of community-based project.

to show that for $p^s = p^m$, we have $f < 0$ if Equation (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:

$$\underline{f} = \frac{h(k)}{m}\left(\frac{z - p^x}{\varphi(k)} + p^x + \rho^s - p^m\right) < 0 \tag{20}$$

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

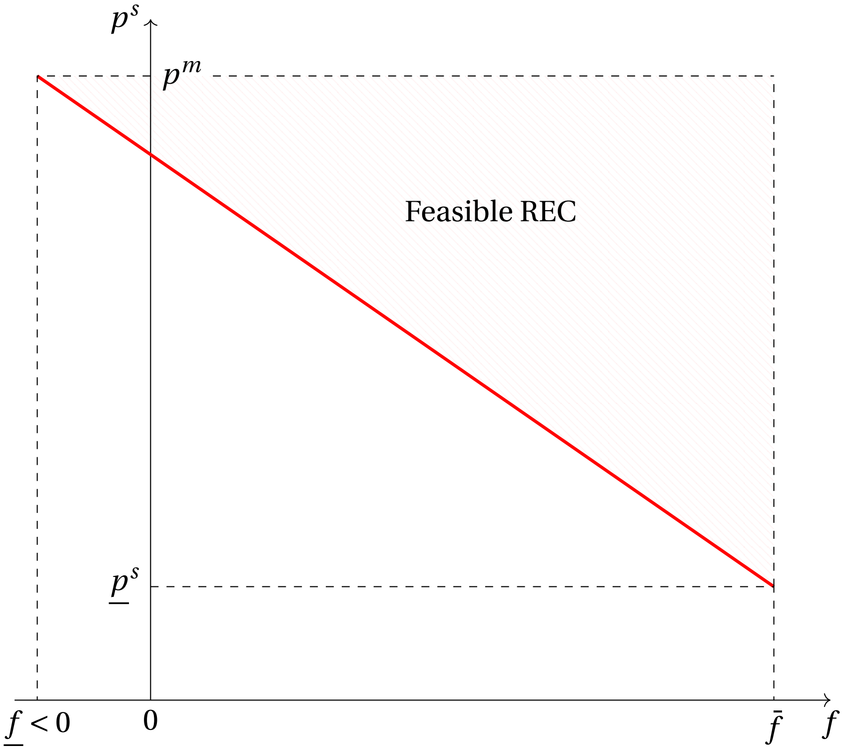

Figure 2: Possible prices and fees in a feasible energy community

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 can achieve will be given by the participation constraint of the member with the lowest allocated self-consumption. Define $\underline{\alpha}$ as the $\min_{i \in M} \alpha_i$.

Lemma 4 *The REC can charge a community price* $p^s \in [\underline{p}^s, p^m]$ *with*

$$\underline{p}^s = p^m + \frac{z - p^x}{\left(1 - m\underline{\alpha}\right)\varphi(k)} - \frac{p^m - p^x - \rho^s}{1 - m\underline{\alpha}},$$

and the corresponding f is given by the zero-profit constraint.

If the community chooses the price $\underline{p}^s$, members have to pay an entry fee equal to $\overline{f} = -\frac{m\underline{\alpha}}{1-m\underline{\alpha}}\underline{f} > 0$.

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, i.e, $p^s = xp^m + (1-x)\underline{p}^s$ and $f = x\underline{f} + (1-x)\overline{f}$, for $x \in [0,1]$. These prices satisfy the participation constraint of all members.

5.2 Choice of capacity by the community

Next we turn to the choice of a capacity and we can show that independently of the community price all individuals prefer the first best capacity, at least under full internalization.

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

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

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

Lemma 5 indicates that the individual share, $A_i(x)$, is independent of the level of production k. Then irrespective the internal organization of the community, each member have benefits aligned with the value created by the community. This implies that all members agree on a choice of the capacity that maximizes v.

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 to choose the first best investment level.

Proposition 3 *With a Coasian grid tariff and a competitive environment with carbon internalization, the community chooses the first best investment level k^*.*

This result is a consequence of both the welfare improvement allowed by feasible RECs when full internalization conditions holds (Proposition 1) and a pricing decision rule that allocates the value to members independently of v (Lemma 5). The pricing rule leads to select a price-fee couple on the zero-profit constraint, that 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. Note that whith full internalization, this first best investment level is also the one that maximizes the REC value v given in (12)

5.3 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 price 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 important 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 (19).

We have shown that the exact pricing decision in the REC has no impact on investment decision achieved and therefore the efficiency result when full internalization holds. However, this may have an impact on 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.

5.4 Community size

So far, we considered a community of a given size m and we search 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 local area.

Consider a community with m members, investing to produce 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 the inclusion of 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 in order 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, especially if they apply simple sharing rules. They recommend to share 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 need to know the rules governing the organization of the community and its objective, which is beyond the scope of this paper. Without entering in those considerations, the community can use its prices and the sharing rule to limit participation. Indeed, suppose that the sharing rule is prorata 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 relatively fee. Hence, prices and sharing rules can be used to limit participation, even in a system of open participation.

6 When energy prices do not reflect their cost

Our efficiency results were based on assumptions of cost-reflective grid tariffs, but also a competitive environment with carbon internalization. In this subsection, we relax these last assumptions and show that all RECs are not more efficient.

6.1 Non-competitive markets

Consider the case of imperfectly competitive retail market (along with Coasian tariffs and carbon internalization). Suppose that retailers realize a retail margin[13] $\mu > 0$ 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, Equation (13) no longer coincides with the welfare improvement condition and it is possible to find communities that decrease welfare but that manage to profitably form as the threshold value in Equation (13) decreases. Indeed, now a community can be profitably formed if

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

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

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 much capacities compared to the first-best*

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

6.2 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 Equation (13) again no longer coincides with the welfare improvement condition. Indeed, we have now

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

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 results, not all the communities that improve welfare will form and, those who exist, invest less in capacity than the efficient capacity level.

7 Extensions

In order to extend the scope of our main results described in Proposition 1 to 3, we extend our model by considering REC with multiple production technologies and storage.

7.1 Multiple production technologies

We consider two production technologies 1 and 2 (solar and wind). We suppose that it costs $z_i k_i$ for a production of k_i MWh with technology $i = 1, 2$. 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.

Assumption 5 *$h(k_1,k_2)$ with (1) $\frac{\partial h}{\partial k_i} > 0$ for $i = 1,2$, (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 capacity installed for each technologies 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.[14] Part (4) indicates that if only one technology installed we turn back in our main setting, analyzed since Section 2. Parts (1) and (4) together imply that, with a second technology $k_j > 0$, the self-consumption will be always higher than with with a single technology for a given production level k_i: $h(k_i,k_j) > h(k_i)$.

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

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

A community producing K increases the welfare if:

$$\theta^m(Q_N - K) + \theta^x(K - h(\mathbf{k})) + \theta^s h(\mathbf{k}) + nF + (c+\delta)(Q_N - K) + z_1k_1 + z_2k_2 \leq (c+\delta+\theta^m)Q_N + nF$$

So the counterpart of (8) is

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

where $\sigma_i = \frac{k_i}{K}$ 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 RHS is not independent of **k**, Equation (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 **k** allows for high levels of self-consumption rates.

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

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

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

In a multiple technology REC, the first best investments are such that[15]

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

which writes

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

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

$$k_i^{**} < k_i^{*}$$

Lemma 9 stems from the substitutability between technologies assumption. Despite lower investments in each technology, the possibility to combine 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 show 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:

$$\begin{aligned} (p^m - \rho^s - p^x) \frac{\partial h(\mathbf{k})}{\partial k_1} &= z_1 - p^x \\ (p^m - \rho^s - p^x) \frac{\partial h(\mathbf{k})}{\partial k_2} &= z_2 - p^x \end{aligned}$$

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

7.2 Storage

Usually, we imagine that REC will be able to complement their DPU investments by installing devices that allow to 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

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

the batteries of electric vehicles (see for example Kempton and Tomic (2005) or more recently Hoarau and Perez (2018)). A storage device is used to transform exports in 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. Suppose that the community can invest in a battery with capacity s at cost ξs. The battery will increase the community 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 increases 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) find 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

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

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

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

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

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

With storage, the REC feasibility condition writes

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

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:

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

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

8 Conclusion and policy implications

Renewable energy communities have received a large amount of attention from policymakers in the political world and in the regulatory arena. In this work, we first show that, for them 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 form of 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 and with appropriately designed grid tariffs.

In the energy regulatory arena, it is important to keep in mind that one of the key advantage 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 supports 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 will in large part depend on the precise size of the decrease in the energy system costs created by more collective self-consumption. At this stage, little research has been done on this issue. This is a key empirical question where future works should focus on in order to further refine our regulatory recommendation.

One key topic has not been not covered in this work and is also one of its key limitation. It is inclusiveness. Renewables are a long-lived asset and they require a large up-front investment. Renters or low-income households might feel set aside by these communities. Even if, as discussed in Section 5, 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 are 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 important issue.

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A Proofs

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

$$h(x) \leq h'(k)\,(x-k) + h(k)$$

Taking $x=0$, 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).

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

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

And from Lemma 2, we identify $\varphi(\bar{k})$ in the RHS. 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 Proposition 2. Plugging (18) in both (16) and (17) leads respectively to

$$\rho^s = \left(\rho^x - \left(\beta + \theta^x\right)\right) \frac{z + \theta^s - (c + \delta + \theta^m)}{z + \theta^x - (c + \delta + \theta^m)} + \beta + \theta^s$$

and

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

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

Proof of Lemma 4. Binding (10) for $\alpha = \underline{\alpha}$ yields $f = (p^m - p^s)\underline{\alpha}h(k)$ which in (19) gives $\underline{p}^s$ after isolating p^s.

Proof of Lemma 5. Binding the zero profit constraint (9) we have

$$\begin{aligned} f &= -\frac{1}{m}\{(p^s - \rho^s)h(k) + p^x(k - h(k)) - zk\} \\ &= -\frac{1}{m}\{v + (p^s - p^m)h(k)\} \end{aligned}$$

and taking participation constraints (10),

$$B_i = \left(\frac{1}{m} - \alpha_i\right)(p^s - p^m)h(k) + \frac{1}{m}v \tag{23}$$

From Lemma 4, one can write that $p_s = xp^m + (1-x)\,\underline{p}^s$ for any $x \in [0,1]$ that is

$$p^s = p^m + \frac{(1-x)}{1 - m\underline{\alpha}}\left[\frac{z - p^x}{\varphi(k)} - \left(p^m - p^x - \rho^s\right)\right] = p^m - \frac{(1-x)}{\left(1 - m\underline{\alpha}\right)h\left(k\right)}v$$

Putting p^s in (23) and collecting the terms leads to the result.

Proof of Proposition 3. 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. Using (23) and substituting v from (12), the benefit B_i for each member writes

$$B_i = \left(\frac{1}{m} - \alpha_i\right)h(k)p^s + \left\{p^m\alpha_i - \frac{1}{m}\left(\rho^s + p^x\right)\right\}h(k) + \frac{1}{m}\left(p^x - z\right)k$$

It is linear in p^s. As $p_s \in [\underline{p}^s, p^m]$, the result stems straightforwardly from Lemma 4.

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

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

where $\varphi(k_\mu) < \varphi(\bar{k})$, then of RECs such that $k \le k_\mu$ 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.

B 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[16] 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. Figures 3 and 4 illustrate Assumption 1 and Lemma 1 respectively.

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%

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

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[16] https://www.synergrid.be/fr/centre-de-documentation/statistiques-et-donnees/profils-slp-spp-rlp

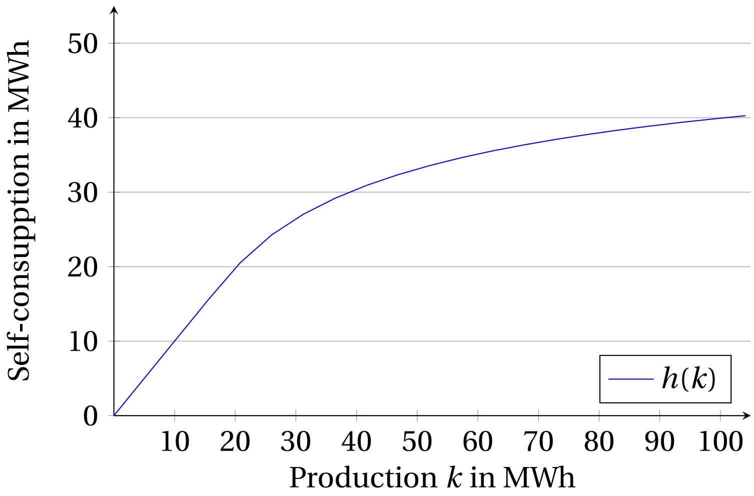

Figure 3: Self-consumption $h(k)$

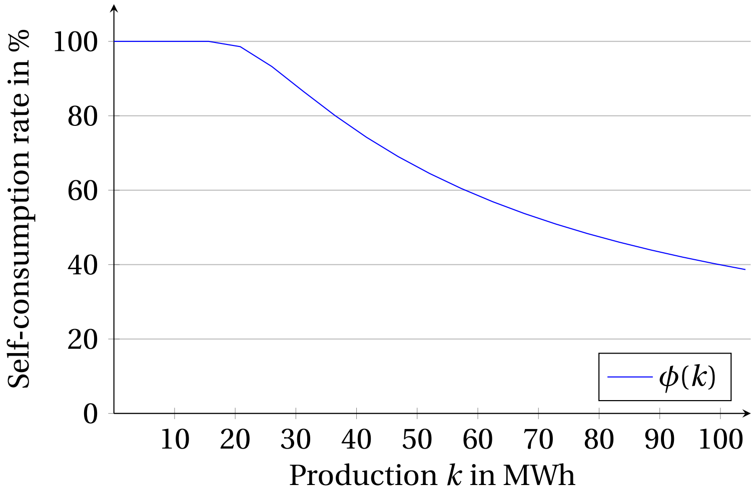

Figure 4: Self-consumption rate $\phi(k)$