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Dynamic Choice of Renewable Energy Communities⋆

Stefano Clò[a] and Gianluca Iannucci[a,*] Alessandro Tampieri[b,c]

[a]Department of Economics and Management, University of Florence, Italy

[b]Department of Economics, University of Modena and Reggio Emilia, Italy

[c]CREA, University of Luxembourg, Luxembourg

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Abstract

This paper compares two forms of Renewable Energy Communities by assessing their impact on long-run social welfare from the perspective of a local public administration. By maximising the intertemporal utility of a representative prosumer, we assess how different REC organisations affect utility under different energy market, incentive and technology conditions. The results show that while consumption and pollution levels remain constant across REC types, differences in prosumers' utility arise due to different financial costs and benefits. In particular, high energy market prices, higher incentive levels and increased energy capacity favour bottom-up RECs, while higher coordination costs and higher prosumer incentive weights favour top-down RECs. Our findings highlight the economic trade-offs that influence REC adoption decisions.

Keywords: Energy community, Mean-variance expected utility, Optimal choice.

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*Corresponding author. Via delle Pandette 9, I-50127 Florence, Italy. *E-mail addresses*: `stefano.clo@unifi.it` (S. Clò), `gianluca.iannucci@unifi.it` (G. Iannucci), `alessandro.tampieri@unimore.it` (A. Tampieri).

1 Introduction

The European Climate Law sets a legally binding target for the European Union to become climate neutral by 2050.[1] Replacing fossil fuel-based technologies with zero marginal cost renewable energy sources (RES) would bring social, environmental and economic benefits, including the reduction of greenhouse gas emissions and local pollutants, increased energy security due to reduced energy dependence on fossil resources, and a decrease in electricity prices (Gelabert et al., 2011, Clò et al., 2015).

Although renewables are now an economically viable alternative to fossil fuels, investment is still significantly low compared to the EU's 2030 targets.[2] The literature has identified three main barriers to the diffusion of RES, which are more relevant for utility-scale plants, namely, big-size plants which are installed by energy companies with the main purpose of selling energy in the wholesale market. The first barrier is known as the "cannibalisation effect": an increase in RES generation lowers energy prices, causing a marginal reduction in the RES' economic returns. This pushes RES away from grid parity, undermining their competitiveness (Clò and D'Adamo, 2015, Prol et al., 2020).[3] A second major obstacle to the development of renewable energy is the social opposition on behalf of local communities, which are called to bear the negative external effects stemming from the installation of utility-scale plants without participating to the resulting economic benefits (Meyerhoff et al., 2010, Groth and Vogt, 2014). Finally, utility-scale plants must undergo lengthy and costly authorisation procedures (European Commission, 2020, Daniele et al., 2023).

The identified barriers are less relevant to energy *prosumers*: mainly households and small and medium enterprises which install small and medium-sized plants to self-produce and self-consume energy.[4] In light of this comparative advantage, the RED II Directive (European

[1]Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law').

[2]To meet the EU's 2030 targets, around 50 GW/year of solar PV capacity will need to be installed in the period 2024-2030, compared to an average of 14 GW/year installed in the period 2013-2022. For more details on the EU 2030 target, see EU Solar Energy.

[3]This negative relationship becomes stronger as the penetration of RES in the energy mix increases, discouraging further deployment of renewable sources.

[4]Due to their limited size, small-scale installations undergo lighter authorisation procedures. Having limited external effects, they are less likely to face social opposition. Moreover, being installed for self-consumption purposes, they are less exposed to the cannibalisation effect.

Parliament and Council of the European Union, 2018) aims at supporting the development of a small-scale RES plants by introducing the Renewable Energy Communities (RECs) within the European legislation. RECs are a collective initiative based on open and voluntary participation where individuals, firms or local authorities jointly produce, share and manage energy generated by small-medium scale renewable plants.

RECs are designed with the intent of sharing the economic and social benefits associated with renewable energy projects within the local communities that develop them.[5] This lowers the risk of social opposition. Moreover, RECs can favour an optimisation of energy use with a reduced impact on the electricity system. For this purpose, many countries grant to small-scale RECs an economic incentive which is proportional to the amount of energy that is shared within the community, that is that energy that is simultaneously produced and consumed at a local level.[6]

In light of these benefits, RECs are increasingly identified as one of the most relevant channels to favour RES adoption. Therefore, defining the most suited RECs' organisational model will be crucial to promoting their diffusion. So far, the literature on RECs has identified two main organisational models: bottom-up and top-down (see, among others, Candelise and Ruggieri, 2020, Tarpani et al., 2022, Ghiani et al., 2022, Bashi et al., 2023, Wierling et al., 2023 and De Vidovich et al., 2023).[7]

A bottom-up REC is organised and driven primarily by local citizens, community groups or grassroots organisations. In this approach, community members are the key decision-makers and typically focus on local benefits such as environmental sustainability, social cohesion and economic resilience. These communities are often driven by local people's desire to have more control over their energy supply and to benefit directly from renewable energy resources (Seyfang et al., 2013).

A top-down REC is established and led by larger organisations, such as local governments, utilities or private companies. In this model, decisions are made by the leading organisation,

[5]Thanks to local energy sharing, RECs members are less exposed to the risk of sharp spikes in energy prices and to increased price volatility, as experienced during the recent energy crisis exacerbated by the Ukraine war.

[6]In a REC, small-scale installations are located near consumers. This geographical proximity reduces the need to transport electricity over long distances, minimizing the costs associated to transmission losses and the risk of grid congestion Couraud et al. (2023). Moreover, when much of the energy produced is consumed on-site, the amount of electricity injected into the grid is reduced, avoiding excessive demand spikes and minimizing the electricity balancing costs (Clò and Fumagalli, 2019).

[7]Tatti et al. (2023) proposes a third type, called the "energy/technical operator driven model".

with less direct input from local community members. The primary aim is often to meet wider policy objectives, such as increasing the penetration of renewable energy, achieving regulatory compliance or meeting corporate social responsibility (CSR) objectives (Walker and Devine-Wright, 2008).

In this paper we evaluate these two forms of RECs by comparing the resulting long-run social welfare of a local community that adopts a bottom up or top down REC organisation. In particular, we compare the optimal intertemporal utility of a representative prosumer in the two alternative cases. The prosumer obtains the energy produced by the REC and the market, pays a participation cost to the REC and receives financial incentives according to the REC type. Finally, the prosumer faces a disutility due to pollution from the emissions required to produce energy from the market.

In our modelling, the introduction of a bottom-up REC requires prosumers to pay an installation and coordination cost that depends on their number. They may also directly consume some of the energy produced by the REC without paying for it. In contrast, the introduction of a top-down REC is managed by a utility company. It requires prosumers to pay an associated cost and to pay for the energy produced by the REC at a price discounted by the incentives. In addition, prosumers share the government incentives with the utility company, at a fixed weight.

We find that the steady state levels of consumption and pollution are the same in the two types of REC. Nevertheless, the different REC organisations have different impacts on the prosumer's utility depending on the energy market conditions, the incentive conditions and the technology conditions.

In terms of energy market conditions, if the expected energy market price tends to be high, then the bottom-up REC type yields a higher expected utility, and *vice versa*. In addition, an increase in the volatility of the energy price favours the bottom-up REC type. Regarding the incentive conditions, an increase in them favours the bottom-up REC type, while an increase in the weight of the incentive to prosumers favours the top-down REC type.

Regarding the technology conditions, an increase in the energy capacity of the REC favours the Bottom-Up choice. Finally, if the coordination costs dominate in the bottom-up REC, then increasing the number of REC participants favours the top-down choice. These results seem quite intuitive: in general, the difference in expected utility is not driven by differences in consumption or pollution levels, but by differences in terms of financial cost-benefits that make one type of REC cheaper than the other.

The remainder of the paper is structured as follows. Section 2 develops the theoretical model. Section 3 derives the steady state of the economy with bottom-up and top-down REC types, respectively, and compares them in terms of consumption and pollution outcomes. Section 4 analyses the different characteristics of equilibria according to market, incentive and technology conditions. Section 5 concludes.

2 The model

Consider a local communities composed of n prosumers, who consume energy c and suffer from pollution s. In this economy, we evaluate the establishment of a REC and they can choose between two alternative REC types: Bottom-up (B) and Top-down (T).

We compare them from a social welfare perspective, by analyzing the long run effects on the expected utility of a representative prosumer of implementing each REC type. Since, as it will be clear below, a prosumer internalises the pollution damage (Forster, 1980), in our framework the indirect expected utility also represents a measure of social welfare.

Since we focus on the prosumer's choice, we assume a given level of production capacity θ equal to both REC types. Once installed, both RECs will provide each prosumer with the right to consume a given amount of energy $\overline{c}$ that increases with the capacity of the REC installment and decreases on the number of REC members: $\overline{c}(n, \theta)$ with $\overline{c}'_{\theta}(\theta, n) > 0$, $\overline{c}'_{n}(\theta, n) < 0$.

Regardless of the type of REC, the central government grants a monetary incentive z for each unit of energy $\overline{c}(n, \theta)$ shared within the REC. Since the incentive has to be distributed among the n REC members, this produces a benefit of $\psi(z, n)\overline{c}(n, \theta)$, with $\psi'_z(z, n) > 0$ and $\psi'_n(z, n) < 0$: the incentive increases with the money allocated by the government and decreases with the number of prosumers in the local community.

REC types

Here we describe the differences between the two REC types, and how they affect the welfare of the representative prosumer.

A B-type REC is a local initiative where community members collaborate to produce, manage, and consume renewable energy. It is usually initiated by local residents and community groups, and requires a high level of local engagement and volunteerism.

This type of REC implies some specific elements: first, REC members have to make a unitary upfront investment $k(n)$ to install a renewable plant, but then they consume the energy $\overline{c}(n, \theta)$ produced by the REC at zero cost. In fact, renewable plants are typically characterised by positive fixed costs and zero marginal production costs. Second, since prosumers directly manage the REC, they also receive the government incentive $\psi(z, n)$. Third, since the REC is managed directly by the community, the representative prosumer faces a coordination cost $k(n) > 0$, which may increase, decrease or be indifferent to the size of the community, $k'(n) \lesseqgtr 0$. The ambiguous sign of the derivative can be interpreted as follows: a type B REC requires (i) installation (fixed) costs and (ii) coordination costs. The former decreases with the number of participants, while the latter increases. Thus, the sign of the derivative ultimately depends on which cost predominates over the other.

Under a T-type REC, the renewable plant is owned and managed by an utility company. Therefore, the REC members are not required to undertake any upfront investment. Local participation may be limited to consultation or minimal involvement. In this case, each prosumer pays a recurring, associative fee $\eta > 0$ to be part of the REC, but REC membership does not imply any coordination cost. On the other side, she also pays the market price for the energy produced by the REC. Finally, in this case the prosumers receive only a share $w \in (0, 1)$ of government incentives, while the share $1 - w$ will be given to the managing utility.

Notice that impliementing a T-type REC necessarily requires the presence of the incentive, otherwise this is never preferable to a situation without REC in place. This is because a prosumer pays the energy at market price like in a hypothetical case with no REC, but it also pays the participation cost. Therefore we assume that participation cost is sufficiently small compared to the incentive weighted for prosumers.

Assumption 1 $\eta < w\psi(z, n)$.

The interpretation is simple: although we consider the size of the incentive as exogenous, the government implements an incentive that ensures the council's participation regardless of the type of REC implemented.

Objective function

The evaluation of the two REC organisations is based on the utility function of the representative prosumer, which exhibits Constant Absolute Risk Aversion (CARA):

$$U_i = -\exp\left(-a v_i\right), \tag{1}$$

where $i \in \{B, T\}$ and $a > 0$ represents the coefficient of risk aversion, and v_i is a function that depends on the specific features of the chosen REC:

$$v_i = u(c_i + \overline{c}(\theta, n)) - \varepsilon_i + y_i \psi(z, n)\overline{c}(\theta, n) - (c_i + \mathbf{1}_{\{i=T\}}\overline{c}(\theta, n))\widetilde{p} - \phi(s_i). \tag{2}$$

In equation (2), $u(c_i + \overline{c}(\theta, n))$ is the utility benefit obtained by energy consumption, with c_i the quantity of energy purchased by the energy market, and $u'_{c_i}(c_i + \overline{c}(\theta, n)) > 0$, $u''_{c_i}(c_i + \overline{c}(\theta, n)) < 0$ (Forster, 1980). The energy market price $\widetilde{p}$ is a random variable distributed according to a normal distribution, with average μ and variance σ^2, $\widetilde{p} \sim \mathcal{N}(\mu, \sigma^2)$. The REC's participation cost is ε_i, where

$$\varepsilon_i = \begin{cases} k(n), & \text{if } i = B, \\ \eta, & \text{if } i = T, \end{cases} \tag{3}$$

while y_i represents the part of the incentive given to a prosumer according to the REC type:

$$y_i = \begin{cases} 1, & \text{if } i = B, \\ w \in (0, 1), & \text{if } i = T. \end{cases} \tag{4}$$

The indicator function $\mathbf{1}_{\{i=T\}}$ takes value 1 if the REC is of T type, and 0 otherwise: in this case indeed, prosumers also pay the quantity of energy produced by the REC system. Finally, $\phi(s_i)$ is the disutility of pollution which, as in Forster (1980), increases in it at an increasing rate: $\phi'(s_i) > 0$ and $\phi''(s_i) > 0$.

Given that the market price is normally distributed, and denoting $\alpha = \frac{a}{2}$, the expected utility of the representative prosumer may be written (see the Appendix for a formal derivation) as

$$EU_i = u(c_i + \bar{c}(\theta, n)) - \varepsilon_i + y_i \psi(z, n)\bar{c}(\theta, n) - (\mu + \alpha\sigma)(c_T + \mathbf{1}_{\{i=T\}}\bar{c}(\theta, n)) - \phi(s_T). \tag{5}$$

The dynamics of pollution

Following Forster (1980), the dynamics of the local community pollution is a linear function of the energy consumed from the market minus its decay:

$$\frac{ds_i}{dt} = \dot{s}_i = \gamma n c_i - \delta s_i, \tag{6}$$

with $i \in \{B, T\}$, $\gamma > 0$, $\delta > 0$, where the parameter γ measures the carbon intensity of the market energy mix, while the parameter δ is the emissions decay rate.

Maximisation

To summarize, the maximisation problem is

$$\begin{aligned}
\max_{c_i} EU_i = \int_0^{+\infty} &[u(c_i + \bar{c}(\theta, n)) - \varepsilon_i + y_i \psi(z, n)\bar{c}(\theta, n) \\
&- (\mu + \alpha\sigma)(c_i + \mathbf{1}_{\{i=T\}}\bar{c}(\theta, n)) - \phi(s_i)]e^{-\rho t}\, dt, \\
\text{s.t. } \dot{s}_i = \gamma n c_i - \delta s_i,\ &s_i \geqslant 0,\ s_i(0) = s_0 > 0,\ c_i \geqslant 0.
\end{aligned}$$

3 Comparison of equilibria

In what follows, we will solve each REC type problems separately, and then we will compare them to see the differences in their implementation.

Begin with the implementation of a B-type REC. The current-value Hamiltonian is:

$$\begin{aligned}
\mathcal{H}_B = &\, u(c_B + \bar{c}(\theta, n)) - k(n) + \psi(z, n)\bar{c}(\theta, n) - (\mu + \alpha\sigma)c_B - \phi(s_B) \\
&+ (\gamma n c_B - \delta s_B)\lambda_B,
\end{aligned} \tag{7}$$

where $\lambda_B \geqslant 0$ is the associated inter-temporal multiplier. The optimality conditions are:

$$\frac{\partial \mathcal{H}_B}{\partial c_B} = u'_{c_B}(c_B + \overline{c}(\theta, n)) - (\mu + \alpha\sigma)c_B + \gamma n \lambda_B = 0, \tag{8}$$

$$\dot{\lambda}_B = \rho\lambda_B - \frac{\partial \mathcal{H}_B}{\partial s_B} = (\delta + \rho)\lambda_B + \phi'(s_B), \tag{9}$$

$$\dot{s}_B = \gamma n c_B - \delta s_B. \tag{10}$$

We can rewrite condition (8) as

$$\gamma n \lambda_B = -[u'_{c_B}(c_B + \overline{c}(\theta, n)) - (\mu + \alpha\sigma)]. \tag{11}$$

Differentiating equation (11) with respect to time (recall that only λ_B and c_B are a function of time), we obtain

$$\gamma n \dot{\lambda}_B = -u''_{c_B}(c_B + \overline{c}(\theta, n))\dot{c}_B \tag{12}$$

Substituting (9) in (12) and re-arranging for the consumption, we obtain the following dynamical system:

$$\begin{aligned} \dot{s}_B &= \gamma n c_B - \delta s_B, \\ \dot{c}_B &= \frac{[u'_{c_B}(c_B + \overline{c}(\theta, n)) - (\mu + \alpha\sigma)](\delta + \rho) - \gamma n \phi'(s_B)}{u''_{c_B}(c_B + \overline{c}(\theta, n))}, \end{aligned} \tag{13}$$

from which we derive the following.

Proposition 1 *The dynamical system (13) admits a unique steady state to which converge the optimal trajectory* $(s^*_B(t), c^*_B(t))$.

Proof. In the plane (s_B, c_B), the isocline $\dot{s}_B = 0$ is a linear function of s_B:

$$\frac{\partial \dot{s}_B = 0}{\partial s_B} = -\delta,$$

while the isocline $\dot{c}_B = 0$ is an increasing function of s_B:

$$\frac{\partial \dot{c}_B = 0}{\partial s_B} = -\frac{\gamma n \phi''(s_B)}{u''_{c_B}(c_B + \overline{c}(\theta, n))}.$$

Therefore, there exists only one steady state given by the intersection between the isoclines $\dot{s}_B = 0$ and $\dot{c}_B = 0$, namely where $\dot{s}_B = \dot{c}_B = 0$.

Moreover, the Jacobian matrix

$$\begin{pmatrix} \frac{\partial \dot{s}_B}{\partial s_B} & \frac{\partial \dot{s}_B}{\partial c_B} \\ \\ \frac{\partial \dot{c}_B}{\partial s_B} & \frac{\partial \dot{c}_B}{\partial c_B} \end{pmatrix} = \begin{pmatrix} -\delta < 0 & \gamma n > 0 \\ \\ \frac{-\gamma n \phi''(s_B)}{u''_{c_B}(c_B + \overline{c}(\theta,n))} > 0 & \delta + \rho > 0 \end{pmatrix}$$

has a negative determinant. This implies that the steady state is a saddle point and the optimal trajectory $(s^*_B(t), c^*_B(t))$ is its stable branch. □

Analogously, the current-value Hamiltonian of TD is:

$$\begin{aligned}\mathcal{H}_T &= u(c_T + \overline{c}(\theta,n)) - \eta + w\psi(z,n)\overline{c}(\theta,n) - (\mu + \alpha\sigma)(c_T + \overline{c}(\theta,n)) \\ &\quad - \phi(s_T) + (\gamma n c_T - \delta s_T)\lambda_T\end{aligned}$$

The optimality conditions are:

$$\frac{\partial \mathcal{H}_T}{\partial c_T} = u'_{c_T}(c_T + \overline{c}(\theta,n)) - (\mu + \alpha\sigma) + \gamma n \lambda_T = 0, \tag{14}$$

$$\dot{\lambda}_T = \rho\lambda_T - \frac{\partial \mathcal{H}_T}{\partial s_T} = (\delta + \rho)\lambda_T + \phi'(s_T), \tag{15}$$

$$\dot{s}_T = \gamma n c_T - \delta s_T. \tag{16}$$

Notice that the optimality conditions (14), (15) and (16) are the same as in the bottom up case, from which we may state the following result.

Proposition 2 *At the steady state, the Bottom-Up and Top-Down RECs reach the same production and pollution level. Namely, $c^*_B = c^*_T$ and $s^*_B = s^*_T$.*

This result follows directly from the fact that, in order to compare different REC types from the consumer's perspective, we assume a given renewable installed capacity θ which is equal among the alternative REC's organization models.

4 Comparative dynamics

The fact that the steady-state levels of consumption and pollution are identical with the adoption of both types of REC does not necessarily mean that both are equally desirable. Indeed, they may lead to different levels of welfare. Notice that, since the representative prosumer internalises the pollution damage, in our framework the indirect expected utility at steady state also represents a measure of social welfare.

To verify the REC organisation type desirability, we start from the condition that the two RECs are indeed indifferent from a welfare point of view. It is handy to extract the indifference condition with respect to the average market price: $EU_B^* = EU_T^*$ for $\mu = \widehat{\mu}$, where

$$\widehat{\mu} \equiv \frac{k(n) - (1-w)\psi(z,n)\overline{c}(\theta,n) - \eta - \alpha\sigma\overline{c}(\theta,n)}{\overline{c}(\theta,n)}. \tag{17}$$

Definition 1 *Define $\widehat{\mu}$ as the level of the average market price that makes the prosumer indifferent between adopting a bottom-up or a top-down REC type.*

In our steady-state analysis, we will use $\widehat{\mu}$ as a benchmark to assess which type of REC is more desirable from a welfare perspective under different market, incentive and technology conditions.

4.1 Energy market conditions

To begin with, we examine how the choice of REC type is affected by different market conditions. In particular, the advantage of one type of REC over another depends on the price and volatility of the energy market, as well as risk aversion on the demand side. The next proposition derives a relationship between the level of the average energy price and the preferred type of REC.

Proposition 3 *For $\mu < \widehat{\mu}$ it holds $EU_B^* < EU_T^*$, while for $\mu > \widehat{\mu}$ it holds $EU_B^* > EU_T^*$.*

Proposition 3 follows directly from the indifference condition derived in equation (17). Intuitively, since a top-down organisation of REC requires that the energy price is discounted from the market price, if the latter is particularly high (higher than the threshold) then prosumers would find it convenient to adopt a bottom-up organisation of REC.

We turn now to price volatility. Differentiating $\widehat{\mu}$ with respect to σ, one obtains

$$\frac{\partial \widehat{\mu}}{\partial \sigma} = -\alpha < 0. \tag{18}$$

Equation (18) implies that more volatile energy prices are associated with a lower threshold $\widehat{\mu}$ and in turn that the bottom-up organisation is more convenient for a wider range of average energy prices.

Proposition 4 *The bottom-up organisation of REC is more likely to be desirable with an increase in the volatility of the energy price.*

To conclude, by differentiating the threshold energy price with respect to risk aversion, we get

$$\frac{\partial \widehat{\mu}}{\partial \alpha} = -\sigma < 0, \tag{19}$$

from which it follows that

Proposition 5 *The bottom-up organisation of REC is more likely to be desirable with an increase in the risk aversion of prosumers.*

Intuitively, given that the energy produced in a bottom-up type is not paid by prosumers, more risk-averse individuals would prefer this type of REC organisation to the top-down type.

Taken together, Propositions 3 to 5 highlight the trade-off between the two types of REC: in a bottom-up model, prosumers make a fixed up-front investment but do not pay a price for the energy shared within the REC. Therefore, they implicitly pay a fixed price for this energy. Conversely, in the top-down model, prosumers make no upfront investment but pay a variable price for the energy consumed within the REC. This implies that the desiderability of the bottom-up model increases with the average level of the market price, its volatility and the risk aversion of prosumers.

4.2 Incentives conditions

In this section, we examine the role played by public incentives in determing the most desirable REC organisation type. Again, the results are explored using as a reference the average energy market price that let the representative prosumer be indifferent between REC types. Differentiating $\widehat{\mu}$ with respect to z and w, respectively, we obtain

$$\frac{\partial \widehat{\mu}}{\partial z} = -(1-w)\bar{c}(\theta,n)\psi'_z(z,n) < 0, \tag{20}$$

$$\frac{\partial \widehat{\mu}}{\partial w} = \psi(z,n)\bar{c}(\theta,n) > 0. \tag{21}$$

The signs of (20) and (21) imply the following.

Proposition 6 *The bottom-up organisation of REC is more likely to be desirable with an increase in the public incentives. The top-down organisation of REC is more likely to be desirable with an increase in the weight of the incentive to prosumers.*

Again, the results of Proposition 6 are natural: a higher incentive has a relatively greater impact on prosumers in a bottom-up REC organisation, since they do not have to share the incentives with the utility company. Similarly, increasing the weight of incentives in the top-down type makes this REC organisation relatively more favourable than the bottom-up one, *ceteris paribus*.

4.3 Technology conditions

Next, we analyse the role of technology. Our framework allows us to disentangle the effects of REC production capacity and the cost characteristics of bottom-up REC organisation. Indeed, the cost of implementing a bottom-up REC type includes both installation costs, which decrease with the number of participants, and coordination costs, which increase with the number of participants. Accordingly, the total cost of bottom-up implementation is decreasing ($k'(n) < 0$) or increasing ($k'(n) > 0$) with the number of participants, depending on whether the installation or coordination costs predominate.

As in the previous analysis, we check the effect of changes in technology conditions over the threshold average energy price $\widehat{\mu}$, from which we can determine the change in the desirability of one REC organisation type or the other.

Begin with the REC capacity. Differentiating $\widehat{\mu}$ with respect to θ, we get

$$\frac{\partial \widehat{\mu}}{\partial \theta} = \frac{\{[-(1-w)z - \alpha\sigma]\,\bar{c}(\theta,n) - [k(n) - (1-w)z\bar{c}(\theta,n) - \eta - \alpha\sigma\bar{c}(\theta,n)]\}\bar{c}'_\theta(\theta,n)}{[\bar{c}(\theta,n)]^2} \tag{22}$$

Since $\bar{c}'_\theta(\theta, n) > 0$, then the derivative (22) is always negative, so that we may state the following result.

Proposition 7 *The bottom-up organisation of REC is more likely to be desirable with an increase in the energy production capacity.*

Proposition 7 can be explained by considering that public incentives are proportional to the amount of energy produced by the REC. An increase in production capacity implies an increase in incentives, and since the bottom-up type of organisation puts all the incentives in the hands of the prosumers, an increase in energy production capacity has a relatively higher welfare effect if this organisation is adopted.

We are left with the task to evaluate the bottom line costs. Since they are function of the number of REC participants, it is convenient to evaluate how their number influences the desirability of REC types. Differentiating $\widehat{\mu}$ with respect to n, we get

$$\begin{aligned}\frac{\partial \widehat{\mu}}{\partial n} = & \frac{\{k'(n) - (1-w)[\psi'_n(z,n)\bar{c}(\theta,n) + \psi(z,n)\bar{c}'_n(\theta,n)] - \alpha\sigma\bar{c}'_n(\theta,n)\}\, \bar{c}(\theta,n)}{[\bar{c}(\theta,n)]^2} \\ & - \frac{[k(n) - (1-w)\psi(z,n)\bar{c}(\theta,n) - \eta - \alpha\sigma\bar{c}(\theta,n)]\, \bar{c}'_n(\theta,n)}{[\bar{c}(\theta,n)]^2}\end{aligned} \tag{23}$$

Since $\bar{c}'_n(\theta, n) < 0$ and $\psi'_n(z, n) < 0$, the derivative in (23) is positive if $k'(n) \geqslant 0$, which corresponds to the condition that the increase in coordination costs due to the increase in REC participants more than compensates for the decrease in installation costs. In contrast, if installation costs dominate the coordination costs, $k'(n) < 0$, then it is not clear which REC organisation is preferable.

Proposition 8 *The top-down organisation of REC is more likely to be desirable with an increase in the number of participants if the coordination cost dominates the installation cost.*

The intuition of Proposition 8 is simple: if the costs of installing the bottom-up REC are mainly due to installation costs, then increasing the number of REC participants makes this REC organisation relatively more desirable than the top-down REC organisation. The opposite is true if coordination costs dominate.

5 Concluding remarks

Renewable Energy Communities (RECs) have been established with the aim of promoting the diffusion of medium-small scale renewable energy plants by encouraging active citizen participation through the sharing of energy generation and consumption at a local level. This can potentially overcome some barriers (local social opposition, length of the authorization procedure, cannibalisation effect) that has so far hindered the RES diffusion. Moreover, by ensuring that renewable energy is consumed locally, RECs favour an optimization of energy use, reducing the negative impact that RES can exert on the electricity system, in terms of transmission losses, grid congestion or balancing costs. In light of these potential benefits, it becomes crucial to identify which organization model is more suited to support the RECs' establishment under different market or technological conditions.

In this paper we have compared two forms of RECs, bottom-up and top-down, with the aim of maximising the long-run social welfare of prosumers.

We have found that, while steady-state consumption and pollution levels are identical, the benefits differed depending on market prices, incentives and technology conditions. On the one hand, high market prices, higher incentives and greater energy capacity favour bottom-up RECs, while high coordination costs and greater incentive weighting favour top-down RECs. The differences in benefits are driven by financial cost-benefits that made one type of REC more economically convenient than the other.

The focus of the present analysis was to distinguish the different characteristics of each organisation for a given plant size. Our analysis highlights the trade-off between the two REC-types: under a bottom-up model, citizens incur upfront investment and coordination costs, but implicitly pay a fixed price for the energy shared within the community. Conversely, under the top-down model, consumers do not afford any upfront investment, but pay a variable price for the energy consumed within the REC. This implies that the bottom-up model desirability increases with the market price average level, its volatility and with the consumer's risk aversion.

Another important point is to examine how the type of REC organisation affects the decision on plant size. Intuitively, one might expect the coordination costs of a bottom-up organisation to increase with size, at the point where the top-down organisation becomes more efficient as the number of participants increases. In turn, we might expect different plant sizes depending on the organisation implemented, with different levels of RES produced in equilibrium. Moreover, another potential limit of our research is that it focuses on the consumers' choice, disregarding the role of producers and the related bargaining issues among these economic agents. These interesting topics go beyond the scope of this paper and represent the core for future research.

Appendix

Derivation of the expected utility

Following the normal distribution of the market price, then $\frac{1}{\sigma\sqrt{2\pi}}\int \exp\left(-\frac{(p-\mu)^2}{2\sigma^2}\right) dp = 1$. In addition, the expected utility of the representative prosumer with utility (1) becomes:

$$\begin{aligned} EU_i = & -\frac{1}{\sigma\sqrt{2\pi}}\int \exp\left(-av_i\right)\exp\left(-\frac{(p-\mu)^2}{2\sigma^2}\right) dp \\ = & -\exp\left(u(c_i+\overline{c}(\theta,n)) - \varepsilon_i + y_i\psi(z,n)\overline{c}(\theta,n) - (c_T + \mathbf{1}_{\{i=T\}}\overline{c}(\theta,n))\widetilde{p} - \phi(s_i)\right) a \\ & \left[\frac{1}{\sigma\sqrt{2\pi}}\int \exp\left(-\frac{(p-\mu)^2}{2\sigma^2}\right)\ \mathrm{d}p\right]. \end{aligned}$$

Using the moment-generating function of the normal distribution:

$$E[\exp(X)] = \exp(\mu X + \frac{1}{2}\sigma^2 X^2),$$

and applying this to our term when $X = -a(c_T + \mathbf{1}_{\{i=T\}}\overline{c}(\theta,n))$,

$$EU_i = u(c_i+\overline{c}(\theta,n)) - \varepsilon_i + y_i\psi(z,n)\overline{c}(\theta,n) - a\mu(c_T + \mathbf{1}_{\{i=T\}}\overline{c}(\theta,n)) + \frac{1}{2}a^2\sigma^2(c_T+\overline{c}(\theta,n))^2.$$

Finally, denoting $\alpha = \frac{a}{2}$, using the volatility σ instead of the variance σ^2 for notation reasons, one gets equation (5).

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