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Endogenous Formation of Renewable Energy Communities

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Abstract

This paper explores what drives households to join a Renewable Energy Community (REC) and how these drivers jointly determine the community's endogenous participation. We present a model in which each household decides whether to join the REC or to continue buying energy on the market. REC members receive a share of the clean energy generated collectively by the REC at no direct charge. In return, they incur installation and coordination costs that rise with membership, while benefiting from government incentives. Both REC members and ordinary consumers bear a utility loss from pollution, reflecting the emissions associated with market-supplied energy. We find that households belonging to a REC draw less energy from the conventional market and are therefore less dependent on it. Participation in the REC increases when average market prices rise, market price volatility increases, or funds devoted to incentives become more generous. Our results highlight the REC's role as a risk-hedging mechanism against fluctuations in energy prices.

Keywords: Energy community, Expected utility, Evolutionary game.

JEL classification: C73, Q42, Q53.

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1 Introduction

The 2018 Renewable Energy Directive (RED II, European Parliament and Council of the European Union, 2018) formally allowed European citizens who own renewable energy installations to share locally the surplus of energy they produce and do not self-consume. Complementing this, the Internal Electricity Market Directive (IEM) further reinforced the right of individuals to consume, store, and sell locally generated energy.

These measures paved the way for Renewable Energy Communities (RECs). Based on open and voluntary participation, RECs are collective initiatives where individuals, businesses and local authorities collaborate to produce, manage and share renewable energy within their communities. RECs respond to the growing demand for alternative models for organising and governing energy systems (Van der Schoor et al., 2016). They also increase citizens' and local authorities' involvement in renewable energy projects, thereby contributing to the broader goal of participatory democracy (Caramizaru and Uihlein, 2020).

The expansion of RECs is considered strategically relevant for several reasons. By promoting the local consumption of renewable energy produced by small- to medium-sized installations, RECs help to optimise energy use and mitigate the grid-related challenges that are often associated with large-scale renewable projects. Shared local energy reduces the need for long-distance electricity transmission, thereby cutting network losses and reducing the risk of grid congestion. Furthermore, meeting energy demand close to where it is generated can lower peak demand and reduce the risk of grid overload.

Compared to utility-scale installations, RECs offer distinct advantages that increase their social acceptance. They are generally perceived as participatory initiatives that allow the economic benefits stemming from RES adoption to be shared within local communities, thus increasing social acceptability. Their relatively small size — typically under 1 MW — supports a distributed generation model with minimal local environmental impact and simpler permitting procedures. This makes RECs an attractive solution for accelerating the energy transition while ensuring local benefits and stronger public support.

In a recent paper, Clò et al. (2025) developed a framework that compares the advantages and disadvantages of two type of REC organisations: top-down and bottom-up.[1] A top-down REC is managed by large organisations, mainly utilities or private compa-

[1] This distinction is standard in the environmental literature. See 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). In this literature, Tatti et al. (2023) suggests a different, third type, which they call "energy/technical operator driven model".

nies (Walker and Devine-Wright, 2008), while a bottom-up REC is organised primarily by local citizens or community groups (Seyfang et al., 2013).

Clò et al. (2025) found that, while consumption and emissions remained steady across the various REC models, participants' overall utility diverged due to differing financial costs and benefits. Specifically, bottom-up RECs are favoured when energy market prices are high, subsidies are generous and generation capacity is expanding. Conversely, top-down RECs become more attractive when coordination expenses rise and the proportion of incentives allocated to REC members increases.

A rather strong assumption of Clò et al. (2025) is the fact that the two REC types are exogenous. In particular, in the baseline analysis, top-down and bottom-up RECs have same equal size. This assumption was necessary to compare the other features of each REC type organisation. Along the paper, Clò et al. (2025) later relax this assumption by making the more reasonable assumption that a bottom up organisation is smaller, yet keeping the REC participation as given. The endogeneity of the size in terms of number of participants is particularly relevant for the bottom-up type. Indeed, one would expect the coordination costs of a local community to increase with the number of members of the community. In bottom-up renewable energy communities, each additional member spreads fixed installation costs, increases the community's self-consumption rate, and can boost collective electricity bill savings by over 40% (Belmar et al., 2023). Identifying the determinants of the REC size is essential to design adequate policies and identify the conditions that can foster their future expansion through the voluntary participation of citizens (Karytsas and Theodoropoulou, 2022, Neves et al., 2024).

Studying the endogenous participation of bottom-up Renewable Energy Communities (RECs) is analytically relevant, as their viability depends directly on the number of households that voluntarily choose to participate. Unlike top-down schemes, where the scale of energy infrastructure is predetermined by utilities or municipalities and user participation is incidental to project design, bottom-up RECs rely on active citizen engagement, both financially and organisationally. By contrast, top-down REC models incorporate scale decisions within a single agent. The capacity factor, rather than the number of members, becomes the key design variable, meaning that the elasticity of membership is of secondary importance.

This paper focuses on bottom-up RECs, investigating the factors that influence participation. The aim is to understand how participation in RECs emerges through household engagement and how policies can support their development. We examine a model in which households choose whether to join a REC and become REC members, or to purchase energy from the market only. If a decision is made to participate in the REC, a proportion of the REC member's energy consumption will be met through the internal energy-sharing mechanism. This amount of energy, though generally does not entirely cover a REC member's energy needs, so that they purchase the rest from the market. REC members also pay an installation and coordination cost that is related to their number, and receive financial incentives from the government. Both REC members and consumers in the market face a utility cost of pollution caused by the emissions required by the market to produce energy.

Bottom-up RECs exhibit the strategic membership dynamics familiar from coalition formation and evolutionary game theory. Marginal benefits of joining a group decline as the group grows if the costs of governance increase faster than the gains from sharing. However, positive network externalities, such as peer influence, bill aggregation and joint battery sizing, can create interior Nash equilibria or even tipping-point adoption thresholds. Failing to consider these endogenous feedbacks can result in oversized assets — or worse, the design of tariff structures that become unstable when fewer households enrol than planners anticipated.

The analysis is dynamic: in each time period, every member of the community compares their expected utility of belonging to the REC with their expected utility of not belonging to the REC. In the model, uncertainty is represented by the energy price, which is treated as a random variable. Changes in expected utility over time occur because REC costs and benefits depend on the number of participants. Consequently, the size of the REC evolves dynamically towards a steady state. We study the steady states and their stability conditions, and then analyse the features of the equilibria.

A first, intuitive finding is that REC members purchase a lower level of energy from the market. This result is consistent with recent empirical evidence. Staudt and Richter (2025) analyse the effects of the Landau Microgrid Project (LAMP) on the energy consumption of the involved community over two years. They found that the proportion of demand met by externally procured electricity dropped from 100 % to 69 % of demand, i.e. a 31 % reduction in market purchases for the average participant. Our findings align with existing empirical evidence indicating that greater opportunities for self-consumption can significantly increase willingness to join a REC. For instance, Guetlein and Schleich (2024) conducted a discrete choice experiment with over 1,000 participants and demonstrated that higher self-consumption rates in France strongly increase individuals' intention to become REC members. This suggests that the opportunity to reduce dependency on energy market price dynamics plays a key role in motivating participation. They found that the prospect of self-consuming 35% or 70% of household electricity increased the likelihood of REC participation by 8.9 and 11.8 percentage points respectively. This underlines the importance of policies that facilitate collective self-consumption (Inês et al., 2020, Iskandarova et al., 2022).

Next, our results show that an increase in the average energy price, price volatility and the level of public incentives encourages participation in the REC. This theoretical argument is consistent with previous empirical findings that investment decisions in REC are primarily driven by financial returns (see Bauwens, 2019). We also find that higher capacity favours REC diffusion if the marginal cost of installation is relatively low. Finally, an increase in risk aversion also encourages individuals to join the REC to hedge against price volatility. Overall, our results suggest that REC's participation could help to reduce dependence on the grid and mitigate uncertainty in the energy markets.

This paper is closely related to Clò et al. (2025). The assumptions regarding the behaviour of the market price and the utility function of a REC member belonging to a bottom-up REC type are identical. The differences are as follows. First, Clò et al. (2025) focuses on comparing two REC types, whereas we focus on the bottom-up REC and the decision to join or not to join. Second, the analysis carried out by Clò et al. (2025) compares the long-term outcomes of adopting one of the two types, which involves a dynamic optimisation process. In contrast, the present paper uses evolutionary dynamics to examine individual choice. Thirdly, in Clò et al. (2025), uncertainty was studied through mean-variance utility, whereas here, we adopt a more general expected utility framework. Finally, in Clò et al. (2025), the cost of being part of a bottom-up REC was independent of the REC's production capacity; in contrast, in the present paper, the participation cost and production capacity are related.

The remainder of the paper is structured as follows: Section 2 develops the theoretical model, while Section 3 derives the steady state of the economy and the stability conditions. Section 4 analyses the how the REC participation reacts to changes in REC capacity, energy prices and risk aversion, and Section 5 focuses on the policy implications of our analysis, by studying how changes in the incentives and their introduction influence REC's participation. Section 6 analyses the dynamics of pollution and its level in the steady state, while Section 7 draws conclusions.

2 The model

Consider a local community composed of $n > 0$ households, who consume energy $c \geqslant 0$ and suffer from pollution $s \geqslant 0$. In this economy, the opportunity to establish REC emerges. Each household may choose to join the REC or purchase the energy from the energy market. The expected utility of a household is affected by its decision to join the REC.

2.1 Purchasing energy from the market only

This section analyses the expected utility of a generic consumer who chooses not to join a Renewable Energy Community (REC). The energy market sells energy produced by carbon fossils. The energy market price is a random variable $\widetilde{p}$, and the expected utility of a household that purchase energy from the market is

$$H_m = Eu\left(y_m\right), \tag{1}$$

with

$$y_m = f(c_m) - \widetilde{p}c_m - \phi(s).$$

where $f(c_m)$ is the utility benefit from the consumption of the energy purchased from the market c_m, $\widetilde{p}c_m$ is the total cost of energy and $\phi(s)$ represents the utility cost of pollution. Following Forster (1980) and Clò et al. (2025), we assume that the marginal utility is decreasing in its argument $(u'(\cdot) > 0, u''(\cdot) < 0)$, as well as the marginal benefit to energy consumption$(f'(\cdot) > 0, f''(\cdot) < 0)$, while the utility marginal cost of pollution is decreasing in the level of pollution, $\phi'(s) > 0$, $\phi''(s) < 0$.

2.2 Joining the REC

We denote as $x \in [0, 1]$ the share of households in the community that join the REC, so that their total number is xn. The energy produced by the REC is "clean", and it is insufficient to cover all the energy needs of one household, so that even the members of the REC purchase some energy from the market, which we denote as c_r.[2]

A REC has production capacity denoted as θ. Once installed, it will provide each households joining the REC (also denoted as "REC members") with the right to consume a given level of energy $\overline{c}$ that increases with the capacity of the REC installment and decreases with the number of households joining the REC: $\overline{c}(\theta, xn)$ with $\overline{c}'_\theta(\theta, xn) > 0$, $\overline{c}'_x(\theta, xn) < 0$. Note that variations in consumption levels with respect to capacity and the number of members are both measures of the productivity level of the REC's plant. If the energy obtained by each member from the REC increases significantly with an

[2] This assumption is realistic. For example, when the REC PV plant is not operational, such as during the winter months or in the evening, energy consumption is not covered by the renewable installations of the REC, but is instead supplied by the market.

increase in capacity ($\overline{c}'_\theta(\theta, xn)$) and decreases slightly with an increase in REC members ($\overline{c}'_x(\theta, xn)$), we can infer that the REC plant is highly productive, and *vice versa*.

REC members consume the energy $\overline{c}(\theta, xn)$ produced by the REC at zero cost. Indeed, renewable plants are usually characterised by positive fixed costs and zero marginal production costs. Moreover, REC members must pay an amount k to install the renewable plant, which depends on the REC capacity and the number of participants, $k(\theta, xn)$. In particular, while the cost is increasing in the size, $k'_\theta(\theta, xn) > 0$, it may increase, decrease or be indifferent to the size of the community, $k'_x(\theta, xn) \lesseqqgtr 0$. This ambiguity is given by the fact that, the cost as a function of the number of REC members includes both as an installation (fixed) and coordination costs. The former decreases with the number of participants, while the latter increases.[3] Thus, the sign of the derivative ultimately depends on which cost predominates over the other.

Notice that, while the consumption of energy produced by the REC is free of charge, the implicit price of consuming the REC energy is given by $\frac{k(\theta,xn)}{\overline{c}(\theta,xn)}$, which is deterministic and naturally independent from the energy market forces.

The government confers an incentive $\psi(z)$ for each unit of energy $\overline{c}(\theta, xn)$ shared within the REC. The unit incentive increases with the money allocated by the government z, so that $\psi'_z(z) > 0$. Therefore, the incentive for every REC member corresponds to $\psi(z)\overline{c}(\theta, xn)$. These incentives are consistent with those applied, after the RED II Directive (2018), by some European governments. For instance, the Italian government grants a 20-years unitary incentive of about €110/MWh for electricity "shared" inside the REC, for 20 years (Governo Italiano, 2023), while the Dutch government grants a 15-year operating subsidy: 2025 base rates for PV range from €0.097–0.135 /kWh depending on size and connection type (Rijksdienst voor Ondernemend Nederland, 2023).

Hence, in case a household joins the REC, its expected utility becomes

$$H_r = Eu(y_r), \tag{2}$$

with

$$y_r = f(c_r + \overline{c}(\theta, xn)) - \tilde{p}c_r - \phi(s) - k(\theta, xn) + \psi(z)\overline{c}(\theta, xn).$$

[3] Empirical evidence highlights that coordination costs, organizational complexity, and social dynamics play a critical role in shaping individuals' willingness to join RECs, acting as a potential barrier to the REC diffusion (Sagebiel et al., 2014, Hwang et al., 2024). At the same time, social factors can offset some of these barriers, particularly through trust and shared identity (Bauwens, 2019).

3 Analysis of equilibrium

In this section, we outline the results. We proceed first evaluating the "static equilibrium", namely, the energy consumption choice of every household in every period. Then, we consider the choice of REC participation.

3.1 Static equilibrium: energy consumption

If a household does not belong to the REC, it purchases exclusively energy from the market Its maximisation problem is represented by

$$\max_{c_m} H_m(c_m).$$

The related first order condition is:

$$H'(c_m) = E\left[u'(y_m)(f'(c_m) - \widetilde{p})\right] = 0, \tag{3}$$

while the second order condition amounts to

$$H''(c_m) = E\left[u''(y_m)(f'(c_m) - \widetilde{p})^2 + u'(y_m)f''(c_m)\right]. \tag{4}$$

The functions properties ensure that equation Eq. (4) is negative, and so FOC Eq. (3) admits a unique maximum level of c_m, denoted as c_m^*.

In contrast, if a household is part of the REC, it consumes energy from the REC at no price, and chooses how much energy to consume from the market. Its maximisation problem is thus represented by

$$\max_{c_r} H_r(c_r).$$

The first order condition is now:

$$H'(c_r) = E\left[u'(y_r)(f'(c_r + \overline{c}(\theta, xn)) - \widetilde{p})\right] = 0, \tag{5}$$

and the second order condition is

$$H''(c_r) = E\left[u''(y_r)(f'(c_r + \overline{c}(\theta, xn)) - \widetilde{p})^2 + u'(y_r)f''(c_r + \overline{c}(\theta, xn))\right]. \tag{6}$$

Like before, the functions properties ensure that equation Eq. (6) is negative, and so FOC Eq. (5) admits a unique maximum level of c_r, denoted as c_r^*.

A quick inspection of the two FOCs Eq. (3) and Eq. (5) shows that, since $u'(\cdot) > 0$,

$$f'(c_m) - E\widetilde{p} = f'(c_r + \overline{c}(\theta, xn)) - E\widetilde{p}.$$

Therefore,

$$c_m^* = c_r^* + \overline{c}(\theta, xn).$$

It follows that

Lemma 1. *In each time period, $c_m^* > c_r^*$.*

The result in Lemma 1 is intuitive and in line with empirical evidence (Staudt and Richter, 2025).

3.2 Dynamics

Having obtained the condition for consumption maximisation, we are now able to endogenise the choice of join or not the REC and analyse its effect on pollution level.

3.2.1 The dynamic system

We assume that households compare the expected utility they obtain from being part of the REC or not, based on the proportion of community household in the REC x during the previous time period.

Thus, we adopt the replicator dynamics:

$$\dot{x} = x(1 - x)\Delta H, \tag{7}$$

where

$$\Delta H \equiv H_r^*(x) - H_m^*(x), \tag{8}$$

and the expected utilities $H_r^*(x)$ and $H_m^*(x)$ are determined by consumption optimisation. The differential equation Eq. (7) admits three types of solutions: the corner $x = \{0, 1\}$ in which there is only one type of households, and inner $x \in (0, 1)$ in which there is coexistence between types.

Following Clò et al. (2025), the stock of pollution increases linearly over time with the consumption of the energy purchased by the market, and decreases also linearly by natural decomposition, taken as exogenous:

$$\dot{s} = [xc_r^* - (1 - x)c_m^*]\gamma n - \delta s, \tag{9}$$

where $\gamma > 0$ represents an impact parameter and $\delta \in (0, 1)$ is the decay rate.

3.2.2 Steady states analysis

The inner solution $x \in (0, 1)$ of replicator dynamics Eq. (7) is a vertical line and represents the locus where $\dot{x} = 0$. The number of inner solutions, and so as well as the number of loci $\dot{x} = 0$, is finite. This last point can be shown by relying on Friedman (1991), according to which a dynamic system admits a continuum of steady states if

$$\frac{\partial \dot{x}}{\partial s} - \frac{\partial \dot{s}}{\partial s} = 0 = \frac{\partial \dot{s}}{\partial x} - \frac{\partial \dot{x}}{\partial x}. \tag{10}$$

Since in our dynamical system $\frac{\partial \dot{x}}{\partial s} = 0$ and $\frac{\partial \dot{s}}{\partial s} \neq 0$, the condition in equation Eq. (10) is not satisfied (see the Proof of Proposition 2 in the Appendix for further details), so that the number of inner steady states is finite.

Substituting $c_r^* = c_m^* - \bar{c}(\theta, xn)$, the locus where $\dot{s} = 0$ is

$$s(x) = [c_m^* - x\bar{c}(\theta, xn)]\frac{\gamma n}{\delta}, \tag{11}$$

from which it is easy to see the steady state levels of equilibrium in the two corner solutions:

$$\begin{aligned} s(x = 0) &= s_0 = \frac{\gamma n}{\delta} c_m^*, \\ s(x = 1) &= s_1 = \frac{\gamma n}{\delta} c_r^*. \end{aligned} \tag{12}$$

From the loci analysis we can infer

Proposition 1. *In the plane (x, s), the dynamic system Eq. (7)-Eq. (9) admits three types of steady states*

- $(0, s_0)$ *in which no one joins the REC;*
- $(1, s_1)$ *in which everyone joins the REC;*
- (x^*, s^*)*, with* $x^* \in (0, 1)$ *and* $s^* \in (s_1, s_0)$*, in which the two types coexist (and converge if stable).*

From Proposition 1 we derive all the steady states that might occur theoretically. In practice, we are particularly interested in the analysis of the inner steady state, which is what generally can be found in reality, and thus determines the endogenous size of the REC.

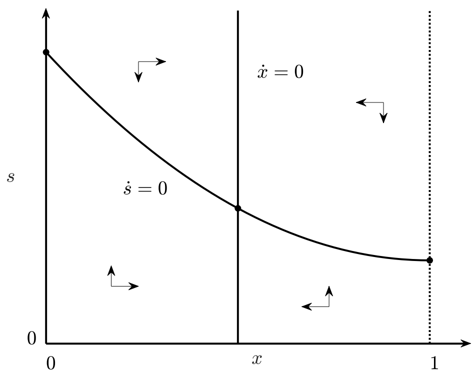
3.2.3 Stability analysis

In this section, we proceed to study the stability of the dynamical system. For convenience, define

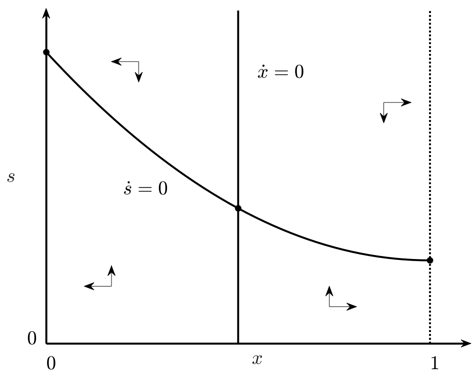
$$\widetilde{k}' \equiv f'(c_r^* + \overline{c}(\theta, xn))\overline{c}'_x(\theta, xn) - \frac{\partial c_r^*}{\partial x} E\widetilde{p} + \psi(z)\overline{c}'_x(\theta, xn),$$

where $\widetilde{k}' < 0$.

Proposition 2. *Assume the existence of at least one inner steady state. If* $k'_x(\theta, xn) > \widetilde{k}'$*, then an inner steady state is stable, while for* $k'_x \leqslant \widetilde{k}'$ *it is unstable (a saddle).*



(a) Stable inner steady state.



(b) Unstable inner steady state.

Figure 1: Examples of dynamics with unique inner steady state.

Note that, since $f'(c_r^* + \overline{c}(\theta, xn))\overline{c}'_x(\theta, xn) < 0$, $\frac{\partial c_r^*}{\partial x}$, and $\phi(z)\overline{c}'_x(\theta, xn) < 0$, then $\widetilde{k}'$ is negative. Therefore, the inner steady state is stable if $k'_x(\theta, xn) > 0$, namely if the coordination cost dominates the instalment cost, or, if $k'_x(\theta, xn) < 0$ is relatively low. Regarding the stability of the corner steady states, the conditions are trivial: the boundary equilibria are attractive when $\Delta H < 0$ in the case $x = 0$ and when $\Delta H > 1$ in the case $x = 1$. Fig. 1 shows an example of stable and unstable inner steady state, respectively, where l'isocline is a decreasing monotone of x (see Section 6 for thorough derivation of this result).

4 Changes in the REC participation

In this section we evaluate how changes in the elements of the economy affect the change in the REC size. We do so by evaluating the variation in the proportion of households that belong to the REC in the inner steady state, (x^*, s^*).

Given that the steady state analysis carried out is implicit, we cannot directly study the derivative of x^* with respect of each element. Instead, we study the partial derivative of the difference between the household's expected utility of being part of the REC or not, that is, ΔH.

Begin by analysing how x^* is affected by changes in REC capacity. Differentiating Eq. (8) with respect to θ, one gets

$$\frac{\partial \Delta H}{\partial \theta} = E\left[u'(y_r^*)(\widetilde{p}\,\overline{c}'_\theta(\theta, xn) - k'_\theta(\theta, xn) + \psi(z)\overline{c}'_\theta(\theta, xn))\right] \leqslant 0, \tag{13}$$

for $k'_\theta(\theta, xn) \leqslant \widehat{k}'$, where

$$\widehat{k}' \equiv [E\widetilde{p} + \psi(z)]\, \overline{c}'_\theta(\theta, xn). \tag{14}$$

The next proposition follows.

Proposition 3. *An increase in the REC capacity increases the share of REC participants if $k'_\theta(\theta, xn) \leqslant \widehat{k}'$. Otherwise, the opposite occurs.*

By Proposition 3, higher capacity favours REC diffusion if the "instalment marginal cost", namely, the increase in cost due to the increase in capacity is not too high (i.e., lower than $\widehat{k}'$). Otherwise, the increased level of REC consumption due to higher capacity does not offset the higher instalment cost.

Second, we evaluate the effects of a change in the energy price over the REC size. Differentiating Eq. (8) with respect to the average energy price, one gets

$$\frac{\partial \Delta H}{\partial E\widetilde{p}} = E[u'(y_r^*)c_r^*] + E[u'(y_m^*)c_m^*] > 0, \tag{15}$$

from which we can state

Proposition 4. *An increase in the average energy price increases the share of REC participants.*

An increase in market prices makes market energy relatively more expensive than REC energy, spurring households to adhere to the REC. These predictions are intuitive and closely align with a well-established body of empirical research that highlights the central role of economic motivations in driving REC participation. Empirical studies conducted across different countries and methodological approaches consistently find that higher expected financial returns significantly increase individuals' willingness to join RECs (Vuichard et al., 2019, de Brauwer and Cohen, 2020, Cohen et al., 2021, Wu et al., 2022, Guetlein and Schleich, 2024) and an increase in electricity prices, coupled with a reduction in electricity costs thanks to self-consumption (Sagebiel et al., 2014, Knoefel et al., 2018, Azarova et al., 2019), can significantly boost individuals' willingness to join RECs. These findings support the idea that participation is often seen as a strategy to achieve tangible economic benefits.

We are left with the task to evaluate how changes in the volatility of the energy prices and the level of risk aversion affect the REC size. In general, we could say that the risk exposition of the non-REC is greater than REC agent, because $c_m^* > c_r^*$. By construction, it is not possible to show the relationship between changes in volatility or risk aversion and the REC size in general.

Our point may yet be supported by studying an example where households are endowed with a CARA utility function.

$$u(y_i) = -\exp(-ay_i),$$

with $i \in \{r, m\}$ and $a > 0$ representing the absolute risk aversion coefficient. We also assume that energy price are normally distributed, $\tilde{p} \sim \mathcal{N}(\mu, \sigma)$. In this context, the optimal households' expected utilities become (see the appendix for a formal derivation):

$$\begin{aligned} H_r^C &= f(c_r^* + \bar{c}(\theta, xn)) - (\mu + \alpha\sigma)c_r^* - \phi(s) - k(\theta, xn) + \psi(z)\bar{c}(\theta, xn), \\ H_m^C &= f(c_m^*) - (\mu + \alpha\sigma)c_m^* - \phi(s), \end{aligned} \tag{16}$$

where superscript C stands for "CARA", $\Delta H^C \equiv H_r^C - H_m^C$, and $\alpha = \frac{a}{2}$. With this specific utility function, the optimisation of energy market consumption is given by the equations Eq. (16)'s first-order conditions (FOCs):

$$\begin{aligned} \frac{\partial H_m^C}{\partial c_m} &= f'(c_m) - (\mu + \alpha\sigma) = 0 \\ \frac{\partial H_r^C}{\partial c_r} &= f'(c_r + \bar{c}(\theta, xn)) - (\mu + \alpha\sigma) = 0 \end{aligned} \tag{17}$$

From Eq. (17), we are able to find the derivatives of c_i^* with respect to volatility,

$$\frac{\partial c_m^*}{\partial \sigma} = \frac{\partial c_r^*}{\partial \sigma} = -\alpha < 0, \tag{18}$$

which amounts to

$$\frac{\partial \Delta H^C}{\partial \sigma} = (c_m^* - c_r^*)\alpha > 0. \tag{19}$$

Similarly, we may obtain the partial derivatives of c_i^* with respect to the degree of risk aversion,

$$\frac{\partial c_m^*}{\partial \alpha} = \frac{\partial c_r^*}{\partial \alpha} = -\sigma < 0, \tag{20}$$

corresponding to

$$\frac{\partial \Delta H^C}{\partial \alpha} = (c_m^* - c_r^*)\sigma > 0, \tag{21}$$

from which we can state

Proposition 5. *Suppose households are endowed with a CARA utility function. Then an increase in the volatility of the energy price or in risk aversion increases the share of REC participants.*

The result in Proposition 5 shows that the REC acts as a hedge against the risk of energy price increases. Indeed, as prices become more volatile or households become more risk-averse, the implicit cost of energy from the REC becomes a safer option. Some empirical studies support the idea that participation in RECs can be driven by the desire to reduce dependence on energy markets and, in particular, to shield oneself from the risks associated with volatile electricity prices, especially among risk-averse individuals (Cardella et al., 2017).

5 Incentives and REC participation

In this section, we study the role played by government incentives. First, we evaluate the effects of changes in public incentives. This is one of the main drivers of energy transition. Differentiation of Eq. (8) with respect to the amount of financial resources devoted to incentives yields

$$\frac{\partial \Delta H}{\partial z} = E[u'(y_r^*)\left(\psi'(z)\bar{c}(\theta, xn)\right)] > 0, \tag{22}$$

from which follows, intuitively,

Proposition 6. *An increase in the public incentives increases the share of REC participants.*

The results in Proposition 6 are supported by the empirical evidence showing the relevance of financial returns to join RECs (Vuichard et al., 2019, de Brauwer and Cohen, 2020, Cohen et al., 2021, Wu et al., 2022, Guetlein and Schleich, 2024). For instance, Bauwens (2019), using a large-scale survey of over 4,000 members of renewable energy cooperatives in Flanders, finds that both higher returns on investment and lower electricity costs are key factors influencing REC membership. Similarly, Hwang et al. (2024) show that consumers tend to favour REC business models that offer higher expected economic returns.

Next, we evaluate how the results change if no incentives are in place, namely, if $z = 0$. In this case H_m remains unchanged, the variation regards only the expected utility of the households who join the REC, $H_r^0 \equiv H_r(z = 0)$:

$$H_r^0 = Eu\big(f(c_r + \bar{c}(\theta, xn)) - \tilde{p}c_r - \phi(s) - k(\theta, xn)\big). \tag{23}$$

Several considerations can be made. First, the absence of incentives favours the pure strategy where no REC is present in the community, $x = 0$. Second, there may exist an $x(z = 0) \in (0, 1)$ such that

$$H_r^0 - H_m = 0, \tag{24}$$

so that an inner equilibrium is ensured also when no incentives are present. Indeed, even without incentives, the risk hedging guaranteed by the fixed, implicit energy price offered by the REC may encourage households to join the scheme.

This point is consistent with some empirical evidence showing that the willingness to engage in local energy initiatives often stems from the desire to reduce dependency on external energy suppliers (Koirala et al., 2018). For instance, Gautier et al. (2019) report that approximately 40% of owners of residential photovoltaic installations engage in self-consumption practices even in the absence of direct financial incentives, reinforcing the idea that autonomy and market independence are powerful drivers of participation.

Third, an immediate comparison between the steady-state household utilities of being part of the REC with and without incentives, H_r^* and H_r^{0*}, reveals that $H_r^{0*} < H_r^*$. It follows that

$$x(z = 0) \in (0, 1) : H_r^{0*} - H_m^* = 0 \ < \ x \in (0, 1) : H_r^* - H_m^* = 0. \tag{25}$$

Hence, even if inner equilibria may occur without incentives, the share of agents who join the REC in this case is smaller.

A final interesting point concerns stability. Define

$$\tilde{k}^{0\prime} \equiv f'(c_r^{0*} + \bar{c}(\theta, xn))\bar{c}'_x(\theta, xn) - \frac{\partial c_r^{0*}}{\partial x} E\tilde{p},$$

where $\widetilde{k}^{0\prime} < 0$, since $f'(c_r^* + \overline{c}(\theta, xn))\overline{c}'_x(\theta, xn) < 0$, and $\frac{\partial c_r^*}{\partial x} > 0$: the consumption of energy from the REC decreases and from the market increases from REC members as their number increase. The interior equilibrium is stable if (see the proof of Proposition 7 for details)

$$k'_x(\theta, xn) > \widetilde{k}^{0\prime}. \tag{26}$$

Since $\widetilde{k}^{0\prime} < 0$, the condition in Eq. (26) can also be satisfied when $k'_x(\theta, xn) < 0$. By contrast, if $k'_x(\theta, xn) > 0$, the equilibrium is always stable, even without incentives.

Proposition 7. *Suppose no REC incentives are in place, and assume the existence of at least one inner steady state. For $k'_x(\theta, xn) > \widetilde{k}^{0\prime}$, an inner steady is stable, while for $k'_x \leqslant \widetilde{k}^{0\prime}$ it is unstable (a saddle).*

The result in Proposition 7 is similar to that in Proposition 2, but now the marginal installation cost must be smaller (in absolute terms) than in the case where incentives are in place. Indeed, a quick comparison shows that $|\widetilde{k}' - \widetilde{k}^{0\prime}| > 0$. Although an inner equilibrium can exist when $k'_x(\theta, xn) < 0$, the condition over the marginal installation cost is smaller. In general, $k'_x(\theta, xn) < 0$ implies that the instalment cost is mainly due to fixed cost, so that it decreases with the number of REC members. Without incentives, the the condition of stability is more stringent.

6 Pollution and REC's participation

In this section, we analyse how the size of the REC affects pollution levels. We begin by comparing the levels of pollution in the two limit cases: when no REC is in place, and when the entire community has joined the REC. By Eq. (12) and Lemma 1, we can conclude that

Proposition 8. *The level of pollution in the community is lower when all the households join the REC than when none of them are part of the REC.*

The result in Proposition 8 is natural, given that the energy produced by the REC does not add up pollution in the environment.

We now analyse the behaviour of the stock of pollution $s(x)$ with respect to changes in $x \in (0, 1)$. This exercise amounts to study the locus $\dot{s} = 0$, with respect to changes in $x \in (0, 1)$. Differentiating Eq. (11) with respect to x, one gets

$$s'(x) = -[\overline{c}(\theta, xn) + x\overline{c}'_x(\theta, xn)]\frac{\gamma n}{\delta}. \tag{27}$$

Since $\overline{c}'_x(\theta, xn)$ is negative, the sign of $s'(x)$ is ambiguous. The intuition is simple. As the proportion of households within the REC increases, on the one hand, it decreases the number of households that purchase energy exclusively from the market. However, each household, for given REC's production capacity, receives a lower amount of energy from the REC, which forces it to purchase more energy from the market. The sign of equation Eq. (27) depends on which of these two effects prevails.

In addition, differentiating Eq. (27) with respect to x, we obtain

$$s''(x) = -[\overline{c}'_x(\theta, xn) + \overline{c}'_x(\theta, xn) + x\overline{c}'(\theta, xn)]\frac{\gamma n}{\delta},$$

which is undoubtely positive, so that the function $s(x)$ is convex. This implies that it admits a minimum point, which we shall denote as $\widehat{x}$. We do not know whether this point lies within the domain $[0, 1]$. Hence, two cases are admissible: (i) $\widehat{x} \in (0, 1)$ and (ii) $\widehat{x} \in [1, +\infty)$. In the first case, the function decreases until $\widehat{x}$, then increases. In the second, the function is monotonically decreasing over the interval $[0, 1]$.

By setting equation Eq. (27) to zero and rearranging, the level of x that minimises pollution requires the following condition

$$\eta \equiv -\frac{\overline{c}'_x(\theta, xn)}{\overline{c}(\theta, xn)}x = 1. \tag{28}$$

In Eq. (28), η represents the level of elasticity of energy received by each REC member $\overline{c}(\theta, xn)$, with respect to the proportion of households in the community participating to the REC, x. The minimum pollution is reached when the elasticity of the REC's capacity with respect to the participation share is equal to 1. We can thus conclude

Proposition 9. *If REC's production capacity is inelastic with respect to REC members ($\eta < 1$), then the steady state level of pollution is decreasing as the proportion of households that join the REC increases.*

Proposition 9 can be read as follows. We know that $\overline{c}'_x(\theta, xn) < 0$, so that the amount of energy received and consumed by each household decreases. In turn, a low elasticity of $\overline{c}(\theta, xn)$ with respect to x indicates that, as the number of REC members increases, the amount of energy received by each household falls little. As a consequence, a low elasticity $\eta < 1$ implies a higher productivity of the REC.

A higher productivity has implications over the level of pollution in the economy. If more households join the REC and their entry affects little the level of energy that each household receives, then the pollution reduction due to the higher number of REC members counterbalances the pollution increase due to the reduction in the energy obtained by each household. In what follows, we will assume that the elasticity is sufficiently low, since in this way the behaviour of the pollution is more consistent with what happens in reality, and the dynamics is monotone for the whole values of x.

Assumption 1. *Let $\eta < 1$.*

We now turn to evaluate how, for given REC size, the level of pollution is affected by the REC's production capacity, the energy prices and the public incentives. Given a certain REC size given by x^*, the locus $\dot{s} = 0$ can be written as:

$$s(x) = [c_m^* - x^*\overline{c}(\theta, nx^*)]\frac{\gamma n}{\delta}, \tag{29}$$

where $x^* \in (0, 1)$ is an attractive steady state.

Begin with studying the changes in production capacity. Differentiating Eq. (29) with respect to θ, we have

$$\frac{\partial s(x)}{\partial \theta} = -\left\{x^*\overline{c}'_\theta(\theta, nx^*) + \left[\overline{c}(\theta, nx^*) + x^*\overline{c}'_{x*}(\theta, nx^*)\right]\frac{\partial x^*}{\partial \theta}\right\}\frac{\gamma n}{\delta}. \tag{30}$$

A quick glance shows that the first part of Eq. (30), $x^*\overline{c}'_\theta(\theta, nx^*)$, is always positive, while the second part shows ambiguity. By Assumption 1, $s(x)$ is a monotonically decreasing function over the interval $[0, 1]$. Then

$$\overline{c}(\theta, nx^*) + x^*\overline{c}'_{x*}(\theta, nx^*) > 0.$$

Moreover, we know by Proposition 3 that $\frac{\partial x^*}{\partial \theta} \geqslant 0$ when $k'_\theta(\theta, nx^*) \leqslant \widehat{k}'$. In this case then, Eq. (30) is negative. The ongoing discussion can be summarised as follows.

Proposition 10. *Let Assumption 1 hold and suppose the marginal instalment cost is sufficiently low, so that $\frac{\partial x^*}{\partial \theta} \geqslant 0$. Then, the steady state level of pollution is decreasing in the REC's capacity. Otherwise, the result is ambiguous.*

The ambiguity in Proposition 10 reflects both the trade off that emerges in the level of pollution with the changes in the REC size, and the trade off that emerges with changes in the REC capacity with the changes in the REC size.

We now turn to the effects on pollution on changes in average energy price. Differentiating Eq. (29) with respect to $E\widetilde{p}$, we obtain

$$\frac{\partial s(x)}{\partial E\widetilde{p}} = \left\{\frac{\partial c_m^*}{\partial E\widetilde{p}} - \left[\overline{c}(\theta, nx^*) + x^*\overline{c}'_{x*}(\theta, nx^*)\right]\frac{\partial x^*}{\partial E\widetilde{p}}\right\}\frac{\gamma n}{\delta}. \tag{31}$$

In equation Eq. (31), $\frac{\partial c_m^*}{\partial E\tilde{p}}$ is negative and $\frac{\partial x^*}{\partial E\tilde{p}}$ is positive and, by Assumption 1, the part in square brackets is also positive, so that equation Eq. (31) is negative. It follows

Proposition 11. *Let Assumption 1 hold. Then, the steady state level of pollution is decreasing in the average energy price.*

Intuitively, an increase in the average energy price reduces the consumption of energy purchased by the market and in turn the level of pollution.

Let us now turn to governmental incentives. Differentiating Eq. (29) with respect to the public resources allocated to incentives, we get

$$\frac{\partial s(x)}{\partial z} = -\left\{\left[\bar{c}(\theta, nx^*) + x^*\bar{c}'_{x^*}(\theta, nx^*)\right]\frac{\partial x^*}{\partial z}\right\}\frac{\gamma n}{\delta} < 0, \tag{32}$$

for $\eta < 1$, thus we can state

Proposition 12. *Let Assumption 1 hold. Then, the steady state level of pollution is decreasing in the level of public incentives.*

We conclude by considering volatility and risk aversion. Like in the previous section, we rely on the example with CARA utility function and normally distributed prices. Notice that, the pollution dynamics are unchanged, what differs are the optimal energy-consumption levels.

We have that

$$\frac{\partial s(x)}{\partial \sigma} = \left\{\frac{\partial c_m^*}{\partial \sigma} - \left[\bar{c}(\theta, nx^*) + x^*\bar{c}'_{x^*}(\theta, nx^*)\right]\frac{\partial x^*}{\partial \sigma}\right\}\frac{\gamma n}{\delta}, \tag{33}$$

and

$$\frac{\partial s(x)}{\partial \alpha} = \left\{\frac{\partial c_m^*}{\partial \alpha} - \left[\bar{c}(\theta, nx^*) + x^*\bar{c}'_{x^*}(\theta, nx^*)\right]\frac{\partial x^*}{\partial \alpha}\right\}\frac{\gamma n}{\delta}. \tag{34}$$

We know that $\frac{\partial c_m^*}{\partial \sigma} < 0$ by equation Eq. (19), and that $\frac{\partial c_m^*}{\partial \alpha} < 0$ by equation Eq. (20). Also, Proposition 5 ensures $\frac{\partial x^*}{\partial \sigma} \geqslant 0$ and $\frac{\partial x^*}{\partial \alpha} \geqslant 0$. It follows that equations Eq. (33) and Eq. (34) are negative.

Proposition 13. *Let Assumption 1 hold and suppose households are endowed with a CARA expected utility function. Then an increase in the energy price volatility or in household risk aversion decreases the steady state level of pollution.*

From Proposition 13, higher volatility or risk aversion encourages households to join the REC because of its risk-hedging effect. This, in turn, reduces the production of polluting energy.

7 Discussion and conclusions

We analysed the factors influencing households' decisions to join Renewable Energy Communities and their impact on a community's equilibrium size. We have developed a model in which each household must choose between becoming a REC member, using some of the energy they produce themselves, or continuing to buy energy from the conventional market.

The focus was on bottom-up REC organisation. Recent empirical evidence highlights the importance of community-led and participatory approaches to overcoming barriers and fostering membership. Experimental studies show that RECs are perceived as being genuinely citizen-driven, rather than being imposed by municipalities, can significantly increase both perceived collective efficacy and willingness to participate (Jans et al., 2024). Furthermore, a recent meta-analysis of 24 quantitative studies (121 effect sizes) reveals that behavioural factors such as trust, environmental attitudes and expected economic benefits are pivotal in determining participation, whereas socio-demographic characteristics lose statistical significance when these behavioural aspects are taken into account (Neves et al., 2024). These findings highlight the importance of understanding and designing RECs as complex social and institutional innovations, rather than merely as technical or regulatory solutions, where participation, governance, and technical scale evolve endogenously.

We have found that REC members reduce their reliance on grid energy, and this effect is more pronounced when wholesale prices increase or government incentives become more generous. Further expansion of generation capacity propels the uptake of RECs, provided that marginal installation costs remain moderate. Finally, we have evaluated the impact of alternative steady states and policy-driven shifts in key parameters on overall pollution levels. One notable aspect of our findings is the REC's role as a risk-hedging mechanism against fluctuations in energy prices. This is particularly important in periods of extreme price volatility.

Our analysis is stricly connected with the current EU institutional contest. The introduction of the 2018 Renewable Energy Directive EU and its subsequent transpositions into national legislation has facilitated the gradual establishment of a clear regulatory framework, including the definition of procedures for setting up RECs and the incentive structures supporting them. In the case of Italy, for example, only around twenty RECs were registered in 2020 (RSE, 2022), but this figure had risen to 168 by 2024 (ESG, 2025). As of March 2025, the GSE portal had recorded 578 operational collective self-consumption initiatives, representing growth of over 240% in the previous year.

Our results on endogenous participation in RECs mirror the significant differences in the number of participants in RECs across the EU. Empirical evidence from over 20 EU case studies shows that citizen-initiated RECs naturally emerge at a range of scales, from small rooftop cooperatives involving fewer than ten households, to village-level wind syndicates. This is because their size evolves in response to local conditions such as social capital, financial capacity, and energy demand profiles rather than following utility-driven technical standards (Caramizaru and Uihlein, 2020). The Italian experience offers a concrete example of this dynamic. As of April 2025, certified RECs in Italy displayed wide variations in technical capacity and membership size. The average installed capacity is 83.7 kW; however, the majority (76%) of communities operate with systems below 50 kW, while only 11% have capacities between 50 and 100 kW. Similarly, the average number of members per REC is 8.2, with almost 77% of communities comprising fewer than ten participants and a very small proportion (less than 2%) exceeding forty members. This strong size heterogeneity highlights the importance of studying the factors influencing households' decisions to join a REC. Participation is shaped not only by economic incentives, but also by social, institutional, and technical conditions that can facilitate or inhibit the expansion of citizen-led energy initiatives. Understanding these drivers is crucial to explaining why RECs differ so widely in scale, and to informing policies that promote more inclusive, decentralised energy models. In terms of both welfare analysis and policy design, modelling the endogenous coalition size in bottom-up RECs captures the interconnection between participation decisions and economic outcomes, which is what fundamentally distinguishes community energy from conventional, top-down infrastructure delivery.

Our findings highlight the key factors that policies should address to promote citizen participation in RECs and support their diffusion by identifying which factors increase the number of REC participants. Firstly, economic incentives are a strong motivator for REC participation. Secondly, lower dependence on external markets and reduced exposure to price volatility encourage involvement, particularly among risk-averse individuals. These findings suggest that enhancing collective self-consumption through technologies such as demand-side management and energy storage could help to align local generation and consumption, thereby increasing self-consumption and reducing reliance on the grid, thus making RECs more attractive. Thirdly, coordination and organisational costs pose significant barriers that may hinder participation in a REC. Therefore, policies supporting effective governance models and lowering transaction costs are crucial. Intermediaries such as ESCOs and local authorities can facilitate coordination, easing administrative burdens. Finally, evidence shows that coordination challenges are less pronounced in localised communities with strong social capital, where shared values foster collective action (Bauwens, 2019). Therefore, social dynamics should complement financial incentives in policy design.

The present analysis can be expanded in a number of ways. First, in some RECs, some of the energy produced is not self-consumed and is instead sold at market rates. The analysis could be expanded to take this into account. Second, we have not yet considered the distinction between "prosumers", i.e. REC members who both produce and consume energy, and consumers within the REC who only consume energy. This distinction exists in some RECs, and analysing their energy exchanges could inform policy. Currently, it is unclear where the exchange component lies. One possible interpretation is from a bargaining perspective, where prosumers and consumers must agree on an internal exchange price for energy. Each party would then compare this price with the alternative of drawing from or selling to the market instead of REC members. A third extension could consider the increase in REC capacity and changes in the number of REC members. One might expect that if the REC's capacity increases and its members reduce market demand, the electricity price would decrease and the incentive to join the REC would progressively decline. These developments are relevant to the design of efficient REC policies and may be explored in future research.

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Appendix

Proof of Proposition 2

The dynamic system is

$$\dot{x} = x(1-x)(H_r^* - H_m^*),$$
$$\dot{s} = [xc_r^* + (1-x)c_m^*]\gamma n - \delta s.$$

from which we obtain the following Jacobian system:

$$\frac{\partial \dot{x}}{\partial x} = (1-2x)(H_r^* - H_m^*) + (x - x^2)\left(\frac{\partial H_r^*}{\partial x} - \frac{\partial H_m^*}{\partial x}\right) \lesseqgtr 0,$$
$$\frac{\partial \dot{x}}{\partial s} = x(1-x)\left\{-E\left[u'(y_r^*)\phi'(s)\right] + E\left[u'(y_m^*)\phi'(s)\right]\right\} = 0,$$
$$\frac{\partial \dot{s}}{\partial x} = \left[c_r^* + x\frac{\partial c_r^*}{\partial x} - c_m^* - x\frac{\partial c_m^*}{\partial x}\right] \lesseqgtr 0,$$
$$\frac{\partial \dot{s}}{\partial s} = \delta < 0.$$

Since $\frac{\partial \dot{x}}{\partial s} = 0$, the derivative of the external function is identical for the two types of households, as it is the same utility function $u(\cdot)$, then the sign of the determinant depends solely on the product of $\frac{\partial \dot{x}}{\partial x}$ and $\frac{\partial \dot{s}}{\partial s}$, and therefore on the (opposite) sign of $\frac{\partial \dot{x}}{\partial x}$. Thus, if $\frac{\partial \dot{x}}{\partial x} < 0$, the determinant is positive. Moreover, if $\frac{\partial \dot{x}}{\partial x} < 0$, the trace is negative and the equilibrium is attractive. Conversely, if $\frac{\partial \dot{x}}{\partial x} > 0$, the determinant is negative and the equilibrium is a saddle. Let us examine $\frac{\partial \dot{x}}{\partial x}$ in detail, i.e., at the different stationary states:

$$\left.\frac{\partial \dot{x}}{\partial x}\right|_{x=0} = H_r^* - H_m^*,$$
$$\left.\frac{\partial \dot{x}}{\partial x}\right|_{x=1} = -(H_r^* - H_m^*),$$
$$\left.\frac{\partial \dot{x}}{\partial x}\right|_{x\in(0,1)} = x(1-x)\left(\frac{\partial H_r^*}{\partial x} - \frac{\partial H_m^*}{\partial x}\right).$$

where

$$\frac{\partial H_r^*}{\partial x} = E\left[u'(y_r^*)\left(f'(c_r^* + \overline{c}(\theta, xn))\overline{c}_x'(\theta, xn) - \tilde{p}\frac{\partial c_r^*}{\partial x} - k_x'(\theta, xn) + \psi(z)\overline{c}_x'(\theta, xn)\right)\right] \lesseqgtr 0,$$
$$\frac{\partial H_m^*}{\partial x} = 0.$$

Note that if $k'_x(\theta, xn) > 0$ then $\frac{\partial H_r^*}{\partial x} < 0$, so the internal equilibrium is always stable. However, $\frac{\partial H_r^*}{\partial x}$ can be negative even when $k'_x(\theta, xn) < 0$, provided it is sufficiently small; more precisely, $\frac{\partial H_r^*}{\partial x} < 0$ if and only if

$$k'_x(\theta, xn) > \widetilde{k}', \tag{35}$$

where

$$\widetilde{k}' \equiv f'(c_r^* + \overline{c}(\theta, xn))\overline{c}'_x(\theta, xn) - \frac{\partial c_r^*}{\partial x} E\widetilde{p} + \psi(z)\overline{c}'_x(\theta, xn).$$

Note that, since $f'(c_r^* + \overline{c}(\theta, xn))\overline{c}'_x(\theta, xn) < 0$, $\frac{\partial c_r^*}{\partial x} > 0$, and $\psi(z)\overline{c}'_x(\theta, xn) < 0$, then $\widetilde{k}'$ is negative.

Expected utility with CARA utility function

Here we assume that the household's utility function is of the Constant Absolute Risk Aversion (CARA) type

$$u_i = -\exp\left(-ay_i\right), \tag{36}$$

where $i \in \{m, r\}$ and $a > 0$ denotes the coefficient of absolute risk aversion. The function y_i depends on whether or not a household joins the REC, and may represent the household's final wealth:

$$\begin{aligned} y_m &= f(c_m) - \widetilde{p}c_m - \phi(s), \\ y_s &= f(c_m + \overline{c}(\theta, xn)) - \widetilde{p}c_r - \phi(s) - k(\theta, xn) + \psi(z)\overline{c}(\theta, xn). \end{aligned} \tag{37}$$

Final wealth y_i can be split into a certain part and an uncertain part, i.e. $y_i = v_i + \widetilde{w}_i$. Rearranging the equations in Eq. (37), we obtain

$$\begin{aligned} v_m &= f(c_m) - \phi(s), \\ \widetilde{w}_m &= -\widetilde{p}c_m, \\ v_r &= f(c_m + \overline{c}(\theta, xn)) - k(\theta, xn) + \psi(z)\overline{c}(\theta, xn), \\ \widetilde{w}_r &= -\widetilde{p}c_r. \end{aligned} \tag{38}$$

We can therefore rewrite a household's utility function in Eq. (36) as

$$u_i = -\Big[\exp\big(-av_i\big)\,\exp\big(-a\widetilde{w}_i\big)\Big]. \tag{39}$$

From Eq. (39), we compute u_i's expected value:

$$\begin{aligned} H_i^C = Eu_i &= -\exp(-av_i)\frac{1}{\sigma\sqrt{2\pi}}\int \exp(-aw_i)\exp\left(-\frac{(w_i-\mu)^2}{2\sigma^2}\right)\,\mathrm{d}w_i \\ &= -\exp(-av_i)\exp\left(-a\left(\mu-\frac{1}{2}a\sigma^2\right)\right)\left[\frac{1}{\sigma\sqrt{2\pi}}\int \exp\left(-\frac{(w_i-(\mu-\frac{1}{2}a\sigma^2))^2}{2\sigma^2}\right)\,\mathrm{d}w_i\right], \end{aligned} \tag{40}$$

where $\mu > 0$ is the mean and $\sigma^2 > 0$ is the variance of $\widetilde{w}_i$. Since $\widetilde{w}_i$ is normally distributed, then

$$\tfrac{1}{\sigma\sqrt{2\pi}}\int \exp(-\tfrac{(w_i-(\mu-\frac{1}{2}a\sigma^2))^2}{2\sigma^2})\,\mathrm{d}w_i = 1,$$

and hence Eq. (40) may be rewritten as

$$\begin{aligned} Eu_i &= -\exp(-av_i)\exp\left(-a\left(\mu-\frac{1}{2}a\sigma^2\right)\right) \\ &= -\exp\left(-av_i - a\left(\mu-\frac{1}{2}a\sigma^2\right)\right). \end{aligned} \tag{41}$$

Substituting $\frac{1}{2}a = \alpha$ into Eq. (41) and expressing uncertainty in terms of volatility σ rather than variance, the household utilities with CARA utility functions become

$$\begin{aligned} H_m^C &= f(c_m) - (\mu+\alpha\sigma)c_m - \phi(s), \\ H_r^C &= f(c_m+\bar{c}(\theta,xn)) - (\mu+\alpha\sigma)c_r - \phi(s) - k(\theta,xn) + \psi(z)\bar{c}(\theta,xn). \end{aligned} \tag{42}$$

Proof of Proposition 7

The dynamic system and the Jacobian system are similar to that in the baseline case, i.e.,

$$\begin{aligned} \dot{x} &= x(1-x)(H_r^{0*} - H_m^{0*}), \\ \dot{s} &= [xc_r^{0*} + (1-x)c_m^{0*}]\gamma n - \delta s. \end{aligned}$$

and

$$
\begin{aligned}
\frac{\partial \dot{x}}{\partial x} &= (1-2x)(H_r^{0*} - H_m^*) + (x - x^2)\left(\frac{\partial H_r^{0*}}{\partial x} - \frac{\partial H_m^*}{\partial x}\right) \lesseqgtr 0, \\
\frac{\partial \dot{x}}{\partial s} &= x(1-x)\left\{-E\left[u'(y_r^{0*})\phi'(s)\right] + E\left[u'(y_m^{0*})\phi'(s)\right]\right\} = 0, \\
\frac{\partial \dot{s}}{\partial x} &= \left[c_r^{0*} + x\frac{\partial c_r^{0*}}{\partial x} - c_m^{0*} - x\frac{\partial c_m^{0*}}{\partial x}\right] \lesseqgtr 0, \\
\frac{\partial \dot{s}}{\partial s} &= \delta < 0.
\end{aligned}
$$

The values of $\frac{\partial \dot{x}}{\partial x}$ at the stationary states are:

$$
\begin{aligned}
\left.\frac{\partial \dot{x}}{\partial x}\right|_{x=0} &= H_r^{0*} - H_m^*, \\
\left.\frac{\partial \dot{x}}{\partial x}\right|_{x=1} &= -(H_r^{0*} - H_m^*), \\
\left.\frac{\partial \dot{x}}{\partial x}\right|_{x\in(0,1)} &= x(1-x)\left(\frac{\partial H_r^{0*}}{\partial x} - \frac{\partial H_m^*}{\partial x}\right),
\end{aligned}
$$

where

$$
\begin{aligned}
\frac{\partial H_r^{0*}}{\partial x} &= E\left[u'(y_r^{0*})\left(f'(c_r^{0*} + \overline{c}(\theta, xn))\overline{c}'_x(\theta, xn)\right) - \widetilde{p}\frac{\partial c_r^{0*}}{\partial x} - k'_x(\theta, xn)\right] \lesseqgtr 0, \\
\frac{\partial H_m^*}{\partial x} &= 0.
\end{aligned}
$$

Note that if $k'_x(\theta, xn) > 0$ then $\frac{\partial H_r^*}{\partial x} < 0$, so the internal equilibrium is always stable. However, $\frac{\partial H_r^*}{\partial x}$ can be negative even when $k'_x(\theta, xn) < 0$, provided it is sufficiently small; more precisely, $\frac{\partial H_r^*}{\partial x} < 0$ if and only if

$$
k'_x(\theta, xn) > \widetilde{k}^{0\prime}, \tag{43}
$$

with

$$
\widetilde{k}^{0\prime} \equiv f'(c_r^{0*} + \overline{c}(\theta, xn))\overline{c}'_x(\theta, xn) - \frac{\partial c_r^{0*}}{\partial x}E\widetilde{p},
$$

where $\widetilde{k}^{0\prime}$ is again negative.

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