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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. 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.

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 REC adoption to be shared within local

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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 types of REC organisations: top-down and bottom-up.[1] A top-down REC is managed by large organisations, mainly utilities or private companies (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 the same size. This assumption was necessary to compare the other features of each REC type organisation. Throughout 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 the 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 for designing 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 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.

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 the willingness to join a REC. For instance, Guetlein and Schleich (2024) conducted a discrete choice experiment with over 1000 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 or in the level of public incentives encourages participation in the REC. This theoretical argument is consistent with previous empirical findings that investment decisions in

[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) suggest a different, third type, which they call "energy/technical operator driven model".

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 participation could help to reduce dependence on the grid and mitigate uncertainty in the energy markets.

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

2. Related literature

The transition to green energy technologies has been widely studied in the field of environmental economics. The existing literature on this topic is vast; here, we focus on recent contributions to applied microeconomic theory, particularly those using game-theoretic models that best align with our paper.

A key focus of this literature is coordination failure as a central barrier to green transitions. Such models formalise the concept of a "tipping point" or critical mass in technology adoption, suggesting that policy interventions may be required to shift expectations or reduce early-mover costs, thereby pushing the system from an inferior to a superior equilibrium.

Gerlagh and van der Heijden (2024) introduce a dynamic three-player coordination game that models the costly transition from a polluting state to a cleaner one. Players must incur upfront costs to adopt green technology, which only becomes profitable if others also switch, thereby mimicking the need for group coherence to initiate a profitable green transition. The study's findings reveal the existence of multiple equilibria: a status quo equilibrium where everyone sticks with brown technology, and an efficient equilibrium where everyone coordinates to adopt green technology.

Dhami and Zeppini (2025) develop a theoretical model of firms choosing between clean and dirty technologies, where increasing returns to adoption (e.g. economies of scale or network externalities) can cause technological lock-in. They show that, even in the absence of external shocks, the long-term outcome is unpredictable and dependent on history – minor initial advantages can tip the equilibrium towards either clean or dirty technology due to self-reinforcing adoption dynamics.

Aissa and Tampieri (2025) analyse the interaction between consumers' environmental concerns and a firm's environmental corporate social responsibility (ECSR) during the transition towards sustainable production. Their findings show that, when green consumers make up a proportion of the population, there are few public incentives to drive the green transition, as social welfare levels out during this process. However, private incentives exist to internalise emissions and proliferate ECSR firms, as profits increase with the proportion of ECSR firms.

Another relevant focus of the analysis of the green transition is the strategic behaviour of firms when it comes to adopting or supplying green technologies. Cohen et al. (2015) develop a model of green product adoption involving multiple competing firms and consumer subsidies. They consider positive externalities of adoption, such as environmental benefits or network effects from increased user numbers, and they treat the government as an additional strategic player that sets subsidy policy. They found that the optimal policy or market design could depend on the size of the externalities: for small network or environmental benefits, a monopoly supplier (perhaps receiving R&D support) might achieve the transition more efficiently. However, for large external benefits, a competitive market with many firms might be preferable for consumer adoption.

Valqui et al. (2023) develop a model in which heterogeneous power companies strategically decide whether to retrofit coal plants to co-fire biomass under policy constraints and carbon prices. Contrary to intuition, their results show that profit-maximising firms choose to retrofit mid-efficiency coal units first, rather than the dirtiest or cleanest units. Under high carbon prices, this can actually increase total emissions because the retrofitted units displace cleaner generation elsewhere in the system.

Our paper is also related to literature on green transitions that focuses on the adoption of subsidies to promote green energy transitions. Langer and Lemoine (2022) analyse the optimal temporal profile of subsidies for a clean, durable technology within a dynamic, game-theoretic model. One surprising outcome of their analysis is that the optimal subsidy may increase over time, which contradicts the idea of front-loaded incentives. This is because early adopters often have the highest willingness to pay (for example, enthusiasts who would buy even with a lower subsidy), whereas later adopters are more price sensitive. The government can price discriminate over time by initially offering low subsidies (allowing early adopters to reveal themselves) and increasing the subsidy later to attract more reluctant adopters.

In the literature on the green transition, the analysis of Renewable Energy Communities is still young, mainly due to the novelty of this kind of organisation. 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) focus 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.

3. The model

Consider a local community composed of $n > 0$, in which each household chooses its energy consumption. Time is continuous and, in each instant, a household consumes energy c. 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.

3.1. 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 fossils fuels. The consumption decision is based on the current value of the energy market price, which is a random variable $\widetilde{p}$, and the expected utility of a household that purchases energy from the market is

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

with

$$y_m = f(c_m) - (\widetilde{p} + \tau)c_m,$$

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 $\tau > 0$ is a unit tax on energy consumption when energy is purchased from the market, because it is polluting. We assume that the marginal utility is decreasing in its argument ($u'(\cdot) > 0, u''(\cdot) < 0$), as well as the marginal benefit of energy consumption ($f'(\cdot) > 0, f''(\cdot) < 0$).

3.2. Joining the REC

We denote by $x \in [0,1]$ 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 household joining the REC (also denoted as "REC members") with the right to consume a given level of energy $\widehat{c}$ that increases with the capacity of the REC installation and decreases with the number of households joining the REC: $\widehat{c}(\theta, xn)$ with $\widehat{c}'_\theta(\theta, xn) > 0$, $\widehat{c}'_x(\theta, xn) < 0$. 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 increase in capacity ($\widehat{c}'_\theta(\theta, xn)$) and decreases slightly with an increase in REC members ($\widehat{c}'_x(\theta, xn)$), we can infer that the REC plant is highly productive, and *vice versa*.

REC members consume the energy $\widehat{c}(\theta, xn)$ 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, $k'_x(\theta, xn) \lesseqgtr 0$. This ambiguity is given by the fact that the cost as a function of the number of REC members includes both installation 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 $\frac{k(\theta,xn)}{\widehat{c}(\theta,xn)}$, which is deterministic and naturally independent of the energy market forces.

The government confers an incentive $\psi(z)$ for each unit of energy $\widehat{c}(\theta, xn)$ 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 $\psi(z)\widehat{c}(\theta, xn)$. The incentive is funded by the government revenue collected by the tax on consumption of polluting energy. Hence, the incentive must align with the government budget constraint:

$$[xc_r^* + (1-x)c_m^*]n\tau \geqslant xn\psi(z)\widehat{c}(\theta, xn), \tag{2}$$

where the tax revenue is represented on the left hand side while the overall incentive is on the right hand side of Eq. (2). 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 per-unit 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).

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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.

3 Empirical evidence highlights that coordination costs, organisational 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).

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

$$H_r = Eu(y_r), \tag{3}$$

with

$$y_r = f(c_r + \hat{c}(\theta, xn)) - (\tilde{p} + \tau)c_r - k(\theta, xn) + \psi(z)\hat{c}(\theta, xn),$$

where $f(c_r + \hat{c}(\theta, xn))$ is the utility benefit from the consumption of the energy purchased from the market c_r and the REC, $(\tilde{p} + \tau)c_r$ is the total cost of energy, including tax. Even in this case, the marginal utility is decreasing in its argument ($u'(\cdot) > 0, u''(\cdot) < 0$), and so is the marginal benefit of energy consumption ($f'(\cdot) > 0, f''(\cdot) < 0$).

4. Analysis of equilibrium

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

4.1. Static equilibrium: energy consumption

If a household does not belong to the REC, it purchases exclusively energy from the market. We assume that the energy consumption is bounded, i.e., $c_i \in [\underline{c}_i, \overline{c}_i] \subset \mathbb{R}_+$, with $i \in \{m, r\}$ and where $\underline{c}_i$ and $\overline{c}_i$ are the minimum and the maximum consumption of energy, respectively. This assumption reflects the fact that there exists a minimum level of consumption ($c_i \geqslant \underline{c}_i$) and the demand for energy is finite ($c_i \leqslant \overline{c}_i$). Its maximisation problem is represented by

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

The related first order condition is:

$$H'_m(c_m) = E[u'(y_m)(f'(c_m) - \tilde{p} - \tau)] = 0. \tag{4}$$

The second derivative of $H_m(c_m)$ with respect to c_m allows us to evaluate the concavity of the function. This is[4]

$$H''_m(c_m) = E\left[u''(y_m)(f'(c_m) - \tilde{p} - \tau)^2 + u'(y_m)f''(c_m)\right]. \tag{5}$$

The functions' properties ensure that (5) is negative; therefore $H_m(c_m)$ admits a unique maximum at the optimal level of c_m over the closed and bounded interval $[\underline{c}_m, \overline{c}_m]$, 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:

$$H'_r(c_r) = E[u'(y_r)(f'(c_r + \hat{c}(\theta, xn)) - \tilde{p} - \tau)] = 0, \tag{6}$$

and the second derivative of $H_r(c_r)$ with respect to c_r yields[5]

$$H''(c_r) = E\left[u''(y_r)(f'(c_r + \hat{c}(\theta, xn)) - \tilde{p} - \tau)^2 + u'(y_r)f''(c_r)\right]. \tag{7}$$

Like before, the functions properties ensure that (7) is negative, hence $H_r(c_r)$ admits a unique maximum point over the closed and bounded interval $c_r \in [\underline{c}_r, \overline{c}_r]$, denoted as c_r^*.

4.2. Dynamics

From condition (2), we can derive the unit tax on polluting energy consumption such that the government budget constraint is binding:

$$\tau = \tau^* \equiv \frac{x\psi(z)\hat{c}(\theta, xn)}{xc_r^* + (1 - x)c_m^*}.$$

Moreover, from the static analysis, the optimal expected utilities of the two types of households are

$$H_r^* = Eu(f(c_r^* + \hat{c}(\theta, xn)) - (\tilde{p} - \tau^*)c_r^* - k(\theta, xn) + \psi(z)\hat{c}(\theta, xn))$$
$$H_m^* = Eu(f(c_m^*) - (\tilde{p} - \tau^*)c_m^*)$$

Having obtained the condition for consumption maximisation, we are now able to endogenise the choice of joining the REC or not. Indeed, these utilities are used by households to decide whether or not to join the REC. Thus, they represent the payoffs associated with the two strategies in the evolutionary game.

[4] Note that $H''_m(c_m) = E[u''(y_m)(f'(c_m) - \tilde{p} - \tau)(f'(c_m) - \tilde{p} - \tau) + u'(y_m)f''(c_m)]$, which, after rearranging may be rewritten as in (5).

[5] Note that $H''_r(c_r) = E[u''(y_r)(f'(c_r + \hat{c}(\theta, xn)) - \tilde{p} - \tau)(f'(c_r + \hat{c}(\theta, xn)) - \tilde{p} - \tau) + u'(y_r)f''(c_r)]$, which, after rearranging may be rewritten as in (7).

4.2.1. The state equation and steady states

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

Thus, we adopt the replicator dynamics:

$$\dot{x} = x(1-x)\Delta H, \tag{8}$$

where

$$\Delta H \equiv H_r^*(x) - H_m^*(x), \tag{9}$$

We are now in a position to outline the possible steady states.

Proposition 1. *The differential equation (8) admits three types of steady states*

- $x = 0$ *in which no one joins the REC;*
- $x = 1$ *in which everyone joins the REC;*
- $x \in (0,1)$*, 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 interested in the analysis of an inner steady state, which is what generally can be found in reality, and thus determines the endogenous size of the REC.

An inner steady state implies $H_r^* = H_m^*$, so that $Eu'(y_r^*) = Eu'(y_m^*)$. A quick inspection of the two FOCs (4) and (6) shows that,

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

Therefore,

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

It follows that

Lemma 1. *In each time period, at an inner steady state, it holds* $c_m^* > c_r^*$.

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

4.2.2. Stability analysis

In this section, we proceed to study the stability of the inner steady state, summarised in the following proposition. For convenience, define

$$\check{k}' = [f'(c_r^* + \hat{c}(\theta, xn)) + \psi(z)]\hat{c}'_x(\theta, xn) + (c_m^* - c_r^*)\frac{\partial \tau^*}{\partial x},$$

where

$$\frac{\partial \tau^*}{\partial x} = \frac{[\hat{c}(\theta, xn) + x\hat{c}'_x(\theta, xn)][xc_r^* + (1-x)c_m^*]\psi(z) + (c_m^* - c_r^*)x\psi(z)\hat{c}(\theta, xn)}{[xc_r^* + (1-x)c_m^*]^2}.$$

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

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 $\Delta H > 0$ in the case $x = 1$. Fig. 1 shows examples of homogeneous stable steady states (Figs. 1(a) and 1(b)) and of stable and unstable inner steady states (Figs. 1(c) and 1(d)).

However, $\frac{\partial \tau^*}{\partial x} > 0$ for $\eta < 1$, where

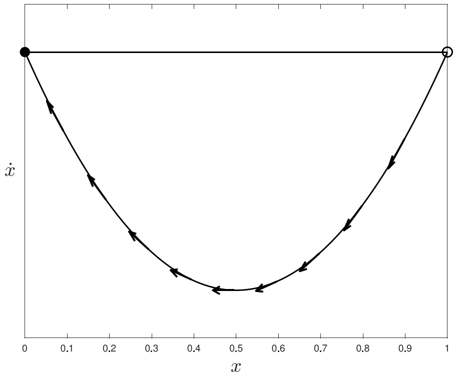
$$\eta \equiv -\frac{\hat{c}'_x(\theta, xn)}{\hat{c}(\theta, xn)}x. \tag{10}$$

In (10), η represents the level of elasticity of energy received by each REC member $\hat{c}(\theta, xn)$, with respect to the proportion of households in the community participating in the REC, x. A low elasticity of $\hat{c}(\theta, xn)$ with respect to x ($\eta < 1$) indicates that, as the number of REC members increases, the amount of energy received by each household falls little. As a consequence, $\eta < 1$ implies a higher productivity of the REC.

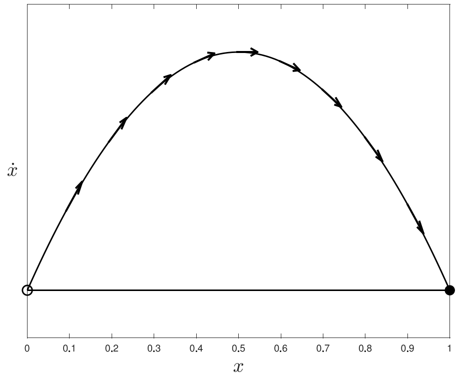
5. Changes in the REC participation

In this section we evaluate how changes in the elements of the economy affect changes in the REC size. We do so by evaluating the variation in the proportion of households that belong to the REC at a stable inner steady state, $x^* \in (0,1)$.

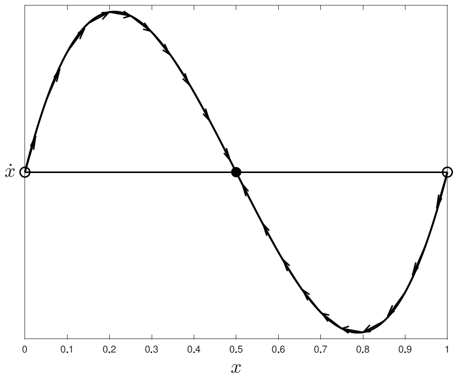
Given that the steady state analysis carried out is implicit, we cannot directly study the derivative of x^* with respect to each element. Instead, we study the partial derivative of the difference between the household's expected utility of being part of the REC or not, that is, ΔH.



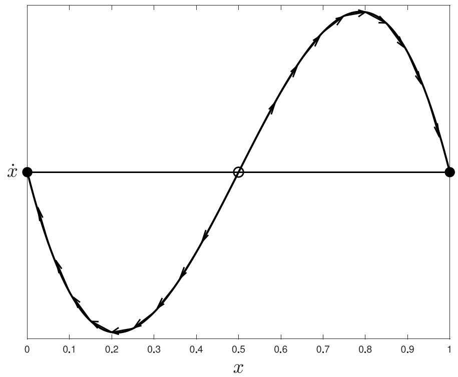
(a) Stable steady state: no household joins the REC.



(b) Stable steady state with all households joining the REC.



(c) Stable inner steady state.



(d) Unstable inner steady state.

Fig. 1. Examples of dynamics; • represents a stable steady state, ◦ an unstable one.

We begin by analysing how x^* is affected by changes in REC capacity. Differentiating (9) with respect to θ, one gets

$$\frac{\partial \Delta H}{\partial \theta} = \frac{\partial H_r^*}{\partial \theta} - \frac{\partial H_m^*}{\partial \theta}, \tag{11}$$

where

$$\frac{\partial H_r^*}{\partial \theta} = E\left[u'(y_r^*)\left(f'(c_r^*\hat{c}(\theta, nx^*))\hat{c}'_\theta(\theta, nx^*) - \frac{\partial \tau^*}{\partial \theta}c_r^* - k'_\theta(\theta, nx^*) + \psi(z)\hat{c}'_\theta(\theta, nx^*)\right)\right], \tag{12}$$

$$\frac{\partial H_m^*}{\partial \theta} = -E\left[u'(y_m^*)\frac{\partial \tau^*}{\partial \theta}c_m^*\right] \tag{13}$$

and

$$\frac{\partial \tau^*}{\partial \theta} = \frac{x^*\psi(z)\hat{c}'_\theta(\theta, nx^*)}{x^*c_r^* + (1-x^*)c_m^*} > 0. \tag{14}$$

Since $\frac{\partial \tau^*}{\partial \theta}$ is positive, it follows that (13) is negative. This implies that an increase in REC capacity leads to an increase in energy consumption tax, and that the optimal expected utility of households not participating in REC decreases. Conversely, (12) can be positive as well as negative. The next proposition outlines the effects of changes in REC capacity on the equilibrium. For convenience, define

$$\hat{k}' \equiv f'(c_r^* + \hat{c}(\theta, nx^*))\hat{c}(\theta, nx^*) + \psi(z)\hat{c}'_\theta(\theta, nx^*) + (c_m^* - c_r^*)\frac{\partial \tau^*}{\partial \theta}. \tag{15}$$

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

By Proposition 3, higher capacity favours REC diffusion if the "installation marginal cost", namely, the increase in cost due to the increase in capacity is not too high (i.e., lower than $\hat{k}'$). Otherwise, the increased level of REC consumption due to higher capacity does not offset the higher installation cost. The fact that a higher production capacity brings about a higher tax is intuitive: more capacity pushes the level of consumption of energy produced by the REC, which in turn increases the level of incentives for each REC member. The effect is, however, tempered by what happens to the expected utility of the non-REC agent.

Second, we evaluate the effects of a change in the energy price on the REC size. Differentiating (9) with respect to the average energy price, one gets

$$\frac{\partial \Delta H^*}{\partial E\widetilde{p}} = E\left[u'(y_m^*)c_m^*\right] - E\left[u'(y_r^*)c_r^*\right]. \tag{16}$$

Given that, in the inner steady state, $H_r^* = H_m^*$ implying $Eu'(y_r^*) = Eu'(y_m^*)$, and so $c_m^* > c_r^*$, then (16) is always positive. Thus 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 join 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 of evaluating 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 exposure of the non-REC is greater than that of a 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 $a > 0$ representing the absolute risk aversion coefficient. We also assume that energy prices are normally distributed, $\widetilde{p} \sim \mathcal{N}(\mu, \sigma)$. In this context, the optimal households' expected utilities become (see the Appendix for a formal derivation):

$$\begin{aligned} H_r^C &= f(c_r^C + \widehat{c}(\theta, xn)) - (\mu + \alpha\sigma c_r^C)c_r^C - \tau c_r^C - k(\theta, xn) + \psi(z)\widehat{c}(\theta, xn), \\ H_m^C &= f(c_m^C) - (\mu + \alpha\sigma c_m^C)c_m^C - \tau c_m^C, \end{aligned} \tag{17}$$

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 Eqs. (17)'s first-order conditions (FOCs):

$$\begin{aligned} \frac{\partial H_r^C}{\partial c_r^C} &= f'(c_r^C + \widehat{c}(\theta, xn)) - \mu - 2\alpha\sigma c_r^C - \tau = 0, \\ \frac{\partial H_m^C}{\partial c_m^C} &= f'(c_m^C) - \mu - 2\alpha\sigma c_m^C - \tau = 0. \end{aligned} \tag{18}$$

From (18), we are able to find the derivatives of optimal H_i^C with respect to volatility,

$$\frac{\partial H_r^C}{\partial c_r^C \partial\sigma} = \frac{\partial H_m^C}{\partial c_m^C \partial\sigma} = -2\alpha c_i^{C*} < 0, \tag{19}$$

which amount to

$$\frac{\partial \Delta H^C}{\partial \sigma} = 2(c_m^{C*} - c_r^{C*})\alpha > 0. \tag{20}$$

Similarly, we may obtain the partial derivatives of optimal H_i^C with respect to the degree of risk aversion,

$$\frac{\partial H_r^C}{\partial c_r \partial\alpha} = \frac{\partial H_m^C}{\partial c_m \partial\alpha} = -2\sigma c_i^{C*} < 0, \tag{21}$$

corresponding to

$$\frac{\partial \Delta H^C}{\partial \alpha} = 2(c_m^{C*} - c_r^{C*})\sigma > 0, \tag{22}$$

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).

6. 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 (9) with respect to the amount of financial resources devoted to incentives yields

$$\frac{\partial \Delta H^*}{\partial z} = \frac{\partial H_r^*}{\partial z} - \frac{\partial H_m^*}{\partial z}, \tag{23}$$

where

$$\frac{\partial H_r^*}{\partial z} = E\left[u'(y_r^*)\left(\psi'(z)\widehat{c}(\theta, nx^*) - \frac{\partial \tau^*}{\partial z}c_r^*\right)\right], \tag{24}$$

$$\frac{\partial H_m^*}{\partial z} = -E\left[u'(y_m^*)\frac{\partial \tau^*}{\partial z}c_m^*\right], \tag{25}$$

and

$$\frac{\partial \tau^*}{\partial z} = \frac{x\psi'(z)\widehat{c}(\theta, nx^*)}{x^*c_r^* + (1-x^*)c_m^*} > 0. \tag{26}$$

Substituting and rearranging, (23) can be rewritten as

$$\frac{\partial \Delta H^*}{\partial z} = \psi'(z)\widehat{c}(\theta, nx^*) + (c_m^* - c_r^*)\frac{\partial \tau^*}{\partial z} > 0, \tag{27}$$

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 from joining 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 4000 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, no taxation is in place, so that, intuitively $c_i^{0*} > c_i^*$, where superscript 0 stands for "zero incentives". In turn, the optimal expected utilities are

$$H_r^{0*} = Eu(f(c_r^{0*} + \widehat{c}(\theta, xn)) - \widetilde{p}c_r^{0*}),$$
$$H_m^{0*} = Eu(f(c_m^{0*}) - \widetilde{p}c_m^{0*}).$$

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

$$H_r^{0*} - H_m^{0*} = 0, \tag{28}$$

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

$$x(z = 0) \in (0, 1) : H_r^{0*} - H_m^{0*} = 0 \ < \ x \in (0, 1) : H_r^* - H_m^* = 0. \tag{29}$$

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

$$\check{k}^{0\prime} \equiv f'(c_r^{0*} + \widehat{c}(\theta, xn))\widehat{c}_x'(\theta, xn)$$

where $\check{k}^{0\prime} < 0$, since $f'(c_r^* + \widehat{c}(\theta, xn))\widehat{c}_x'(\theta, xn) < 0$, 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 increases. The interior equilibrium is stable if (see the proof of Proposition 7 for details)

$$k_x'(\theta, xn) > \check{k}^{0\prime}. \tag{30}$$

Since $\check{k}^{0\prime} < 0$, the condition in (30) 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 $k'_x(\theta, xn) > \check{k}^{0\prime}$, an inner steady state is stable, while for $k'_x \leqslant \check{k}^{0\prime}$ it is unstable.*

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 $|\check{k}' - \check{k}^{0\prime}| > 0$. 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 installation cost is mainly due to fixed costs, so that it decreases with the number of REC members. Without incentives, the condition of stability is more stringent.

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. 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 strictly connected with the current EU institutional context. The introduction of the 2018 EU Renewable Energy Directive 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 Energy Service Companies 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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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Proof of Proposition 2. The dynamic system is

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

where $\Delta H \equiv (H_r^* - H_m^*)$. Differentiating with respect to x, we get:

$$\frac{\partial \dot{x}}{\partial x} = (1-2x)(H_r^* - H_m^*) + (x - x^2)\left(\frac{\partial H_r^*}{\partial x} - \frac{\partial H_m^*}{\partial x}\right).$$

If $\frac{\partial \dot{x}}{\partial x} < 0$ at the steady state then the fixed point is stable, in detail:

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

Differentiating H_r^* and H_m^* with respect to x, one gets

$$\frac{\partial H_r^*}{\partial x} = E\left[u'(y_r^*)\left(f'(c_r^* + \hat{c}(\theta, xn))\hat{c}'_x(\theta, xn) - \frac{\partial \tau^*}{\partial x}c_r^* - k'_x(\theta, xn) + \psi(z)\hat{c}'_x(\theta, xn)\right)\right],$$
$$\frac{\partial H_m^*}{\partial x} = -E\left[u'(y_m^*)\frac{\partial \tau^*}{\partial x}c_m^*\right],$$

where

$$\frac{\partial \tau^*}{\partial x} = \frac{[\hat{c}(\theta, xn) + x\hat{c}'_x(\theta, xn)][xc_r^* + (1-x)c_m^*]\psi(z) + (c_m^* - c_r^*)x\psi(z)\hat{c}(\theta, xn)}{[xc_r^* + (1-x)c_m^*]^2}.$$

Assuming $\frac{\partial \tau^*}{\partial x} > 0$, namely $-\frac{\hat{c}(\theta,xn)}{\hat{c}(\theta,xn)}x < 1$, the necessary and sufficient condition such that $\frac{\partial \Delta H}{\partial x} < 0$ is $k'_x(\theta, xn) > \check{k}'$, where

$$\check{k}' = [f'(c_r^* + \hat{c}(\theta, xn)) + \psi(z)]\hat{c}'_x(\theta, xn) + (c_m^* - c_r^*)\frac{\partial \tau^*}{\partial x} \quad \square$$

Proof of Proposition 3. The replicator dynamics is similar to that in the baseline case, i.e.,

$$\dot{x} = x(1-x)(H_r^{0*} - H_m^{0*}).$$

and

$$\frac{\partial \dot{x}}{\partial x} = (1-2x)(H_r^{0*} - H_m^{*}) + (x - x^2)\left(\frac{\partial H_r^{0*}}{\partial x} - \frac{\partial H_m^{0*}}{\partial x}\right).$$

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

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

where

$$\frac{\partial H_r^{0*}}{\partial x} = E\left[u'(y_r^{0*})\left(f'(c_r^{0*} + \hat{c}(\theta, xn))\hat{c}'_x(\theta, xn)\right) - k'_x(\theta, xn)\right],$$
$$\frac{\partial H_m^{0*}}{\partial x} = 0.$$

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

$$k'_x(\theta, xn) > \check{k}^{0\prime}, \tag{31}$$

with

$$\check{k}^{0\prime} \equiv f'(c_r^{0*} + \hat{c}(\theta, xn))\hat{c}'_x(\theta, xn),$$

where $\check{k}^{0\prime}$ 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,

$$u_i(y_i) = -\exp\left(-a y_i\right), \tag{32}$$

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:

$$\begin{aligned} y_m(c_m, \tilde{p}) &= f(c_m) - (\tilde{p} + \tau)c_m, \\ y_r(c_r, \tilde{p}) &= f(c_r + \hat{c}(\theta, xn)) - (\tilde{p} + \tau)c_r - k(\theta, xn) + \psi(z)\hat{c}(\theta, xn). \end{aligned} \tag{33}$$

Final wealth y_i can be split into a certain part and an uncertain part, i.e. $y_i = v_i + \tilde{w}_i$. Rearranging the equations in (33), we obtain

$$\begin{aligned} v_m &= f(c_m) - \tau c_m, \\ \tilde{w}_m &= -\tilde{p} c_m, \\ v_r &= f(c_m + \hat{c}(\theta, xn)) - \tau c_r - k(\theta, xn) + \psi(z)\hat{c}(\theta, xn), \\ \tilde{w}_r &= -\tilde{p} c_r. \end{aligned} \tag{34}$$

We can therefore rewrite a household's utility function in (32) as

$$u_i(v_i, \tilde{w}_i) = -\left[\exp\left(-a v_i\right)\, \exp\left(-a \tilde{w}_i\right)\right]. \tag{35}$$

From (35), we compute u_i's expected value:

$$\begin{aligned} H_i^C &= -\exp\left(-a v_i\right) \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left(-a w_i\right) \exp\left(-\frac{(w_i - \mu_w)^2}{2\sigma_w^2}\right) \mathrm{d}w_i \\ &= -\exp\left(-a v_i\right) \exp\left(-a\left(\mu_w - \frac{1}{2} a \sigma_w^2\right)\right)\left[\frac{1}{\sigma_w\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left(-\frac{(w_i - (\mu_w - \frac{1}{2} a\sigma_w^2))^2}{2\sigma_w^2}\right) \mathrm{d}w_i\right], \end{aligned} \tag{36}$$

with $\mu_w = \mu c_i > 0$, where $\mu > 0$ is the mean of the random variable, and $\sigma_w^2 = \sigma^2 c_i^2$, where σ^2 is the variance. Since $\tilde{w}_i$ is normally distributed, then

$$\frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left(-\frac{(w_i - (\mu_w - \frac{1}{2} a\sigma_w^2))^2}{2\sigma_w^2}\right) \mathrm{d}w_i = 1$$

and hence (36) may be rewritten as

$$\begin{aligned} E u_i &= -\exp\left(-a v_i\right) \exp\left(-a\left(\mu_w - \frac{1}{2} a \sigma_w^2\right)\right) \\ &= -\exp\left(-a v_i - a\left(\mu_w - \frac{1}{2} a \sigma_w^2\right)\right). \end{aligned} \tag{37}$$

To simplify and compact the notation of the risk premium and the variance, we substitute $\frac{1}{2}a = \alpha$ into the expected utility (37) and we express uncertainty in terms of volatility σ. The household utilities with CARA utility functions become

$$\begin{aligned} H_m^C &= f(c_m) - (\mu + \alpha\sigma c_m)c_m - \tau c_m, \\ H_r^C &= f(c_r + \hat{c}(\theta, xn)) - (\mu + \alpha\sigma c_r)c_r - \tau c_r - k(\theta, xn) + \psi(z)\hat{c}(\theta, xn). \quad \square \end{aligned} \tag{38}$$

Data availability

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

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