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Renewable energy communities, digitalization and information

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Summary

In this work we study the case of agents willing to engage in a Renewable Energy Community (REC). The municipality - being the promoter of the REC - burdens all the investment costs (RE plants, storage, local grid interventions) and entrusts an aggregator of its operation paying a fixed tariff. The latter, acting as a monopolist, is also the sole supplier of energy for the REC's members. The management of the REC requires the collection of energy data from the members to assure its efficient operation on the side of the self-consumption and exchange of energy within it. Such data allow also the identification of the agents' preferences across energy devices and are an additional source of revenues for the aggregator thanks to their sell to third parts. This behaviour translates into a dis-utility the agents, which we call privacy cost. In such a framework, we consider also uncertainty on the side of the investment cost. On the basis of the outcomes of our model, we are able to study the effect of data collection policy performed by the aggregator on the size of the REC, while also accounting for agents' valuation and the role of uncertainty on the investment cost side.

Keywords: Smart Grids, Renewable Energy Sources, Renewable Energy Communities, Prosumers, Peer to Peer Energy Trading, Information, Privacy Costs

JEL Classification: Q42, C61, D81

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Renewable energy communities, digitalization and information

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Abstract

In this work we study the case of agents willing to engage in a Renewable Energy Community (REC). The municipality - being the promoter of the REC - burdens all the investment costs (RE plants, storage, local grid interventions) and entrusts an aggregator of its operation paying a fixed tariff. The latter, acting as a monopolist, is also the sole supplier of energy for the REC's members. The management of the REC requires the collection of energy data from the members to assure its efficient operation on the side of the self-consumption and exchange of energy within it. Such data allow also the identification of the agents' preferences across energy devices and are an additional source of revenues for the aggregator thanks to their sell to third parts. This behaviour translates into a dis-utility the agents, which we call privacy cost. In such a framework, we consider also uncertainty on the side of the investment cost. On the basis of the outcomes of our model, we are able to study the effect of data collection policy performed by the aggregator on the size of the REC, while also accounting for agents' valuation and the role of uncertainty on the investment cost side.

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Acronyms

- A, aggregator
- BRP, balance responsible party
- DER, distributed energy resources
- DG, distributed generators
- DR, demand response
- DSM, demand side management
- DSO, distribution system operator
- G, municipality
- ICT, information and communication technologies
- LFM, local flexible market
- M, municipality
- P2P, peer to peer energy trading
- PMC, private marginal cost
- PV, photo-voltaic
- REC, renewable energy communities
- RE, renewable energy
- RES, renewable energy source
- SG, smart grid
- TSO, transmission system operator

1 Introduction

The need for decarbonization is nowadays widely recognized worldwide: the signing of the Paris Agreement by 196 parties in the 2015 [UN, 2015] gave further impetus to policies aimed at move forward on the path of reducing emissions.

Renewables are considered a major tool to reduce carbon emissions and successfully complete the energy transition process foresaw by policies, especially in the European Union (EU, hereafter). Olivella-Rosell et al. [2018], among others, stated that "decarbonization of the European electricity system has been set in motion with the rapid proliferation of distributed and renewable energy production sources." Again, the EU committed to reduce greenhouse gas emissions by at least 40% until 2030 and this goal is expected to be achieved by installing an a share of 50% of renewables by 2030.

At the same time, the widespread installation of renewable energies sources [Eurostat, 2022] has offered a useful starting point to make the consumer more involved in the management of the energy and electricity system. In the past decade, several countries have begun to consider how to involve citizens more directly in the decarbonization process. The *Clean energy for all Europeans* document [EU, 2019] represents the most up-to-date publication on European energy policy, indicating that consumers and small agents shall become the centre of the electric system. To make the decentralized model effective, however, infrastructures and markets shall be reorganized to increase as much as possible the inclusion of small and medium agents (see Agostini et al. [2021] for an example of the functioning of local markets).

Given the EU policy targets for the diffusion of practices and models for the creation of a more decentralized framework for energy production and management, also local policies' focus switched to the role of consumers, prosumers and their aggregations.

The most discussed aggregation in recent literature is the energy community (EC). EC are defined as "Entities that are entitled to: i) produce, consume, store and sell renewable energy, including through renewables power purchase agreements; ii) share, within the renewable energy community, renewable energy that is produced by the production units owned by that renewable energy community, and maintaining the rights and obligations of the renewable energy community members as customers; iii) access all suitable energy markets both directly or through aggregation in a non-discriminatory manner". [EU, 2018].[1]

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[1] Actually, there are several definitions of energy communities, which can be found in Caramizaru and Uihlein [2021], Olivella-Rosell et al. [2018], among others. In the model setup, we will indicate which are the characteristics of the EC we are analysing.

Energy communities can be seen as a direct descendant of energy cooperatives. Abada et al. [2020] pointed out that "Small energy communities are thus blossoming in many countries: there are currently around 3,000 energy communities across Europe, according to REScoop.eu, and their presence is increasing. Recent policies, however, are structuring and reinforcing their role as part of the energy transition process.

The shape that the EC can take heavily dependent on specific features such as location, endowments, local institutions, type of subjects included in the community, and different issues arise from their establishment. Caramizaru and Uihlein [2021] report a review of the EC projects in Europe, highlighting as major topics of interest customer empowerment and social innovation, the contribution to the expansion of renewables and the impacts on energy systems. Privacy issues are not considered by the report, which mainly focuses on potential benefits for the agents such as self-sufficiency and monetary savings, even if social motivations prevail on monetary and financial advantages in the decision of joining an EC. However, considering possible impacts on the network, the report underlines that EC bring benefits to the network but they can also be challenging for the management of the system. Since the development of EC is still on a preliminary phase, case studies are closer to the experience of energy cooperatives.

EC were analyzed by Lowitzsch et al. [2020] relating their shape to "renewable energy clusters", i.e. clusters where connectivity, complementary energy sources and other relevant characteristics from the technical point of view could represent an optimal aggregation for the development of an EC. Similarly, Volpato et al. [2022] approach EC and REC minimizing operational costs for the network. These perspectives are useful as, despite the great interest for the new aggregations from the sociological point of view (see Prados et al. [2022]), their fundamental role shall be the contribution to higher renewable penetration in local markets, efficiency in their use and reduction of system costs. From an operational point of view, in Olivella-Rosell et al. [2018], we can find examples distinguished into two main categories, namely the peer-to-platform mechanism, a sort of local market platform controlled by a central entity that minimizes the operation cost for each household trader, and the Peer-to-Peer (P2P) negotiation mechanisms, where there is no central entity devoted to the management.[2].

According to Olivella-Rosell et al. [2018] the peer-to-platform approach offers some advantages for trading flexibility in contrast to the classic P2P approach. First of all, decisions on local issues are made centrally, and they are supervised by the aggregator. Thus, the aggregator has a complete EC status overview and can make decisions to benefit the EC as a group, and not every participant individually.

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[2] Consider also Le Cadre and Bedo [2020]

On the contrary, the main advantage of P2P is to avoid the need for a central entity. However, this approach could result in low negotiation power when selling flexibility services to bigger stakeholders, such as balance responsible parties (BRPs), distribution system operators (DSOs) or transmission system operatorors (TSOs). Furthermore, individual market players, like prosumers, would not have access to wholesale markets depending on their size and national regulations. A definition can be found again in Olivella-Rosell et al. [2018] and Jin et al. [2020] as well. The former state that a "local flexibility market (LFM) is an electricity trading platform to sell and buy flexibility within the local energy community". They identify the aggregator as the entity supporting the LFM operation, providing this trading platform for sharing data, exchanging flexibility and scheduling flexible devices. In some sense, the aggregator is the EC facilitator. On the other hand, such role leads to the arising of actions for the support, and boosting, of local interaction, so that flexibility is increased.

Local Energy Markets[3] and P2P are opposed to the actual centralized structure, and in line with the expectations of a more participated market. Beyond the operational mechanism of the EC, we can say that it can have several organizational models and relate on the territory with different agents. The participation of the EC in the LFM is instead an aspect that must always be considered, even when the objective of the community is to maximize self-consumption and reduce the interaction with the network to the minimum. This paper analyses a case where the EC is managed by a service company that offers individual members energy management services and software, combined with devices as well, to increase energy self-consumption. This service company can be seen as an Aggregator, as defined in Khojasteh et al. [2022]. The EC participants sign a contract with the aggregator to benefit from the management services and energy supply, while the investment in renewable energy production plants is borne by a local institution, i.e. a municipality. As later described, the municipality is the promoter of the REC and the bargaining for the establishment of prices and conditions of the service will take place between the municipality and the aggregator.

We said the municipality is the local promoter of the REC. This framework is reasonable as municipalities might have already invested or will invest in renewable energy power plants. Municipalities can be seen as natural coordinators for collective investments, but still the management of the service shall often be delegated to a third party. The model of concession to a specialized company, indeed, overcomes possible limits of knowledge and technology of the municipalities.

The role of municipalities in the energy transition projects is linked to the development of collaborations

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[3] We can say that they are quite the same of LFM

with private companies specialized in the field, recalling the concept of Public Private Partnerships (PPP), as defined in Engel et al. [2008]. More specifically, Carbonara and Costantino [2015] identified the role of PPP in energy efficiency projects.

In our framework, what is offered to private energy consumers is to be part of the REC. Moreover, once they become members, they are also required to share data on their energy consumer habits across energy devices and, of course, related timing as well, so that the REC can operate in the most efficient manner. Alongside the effects on the energy management from both the private and the collective point of view, the participation to an EC raises privacy costs for the agents. Privacy costs are widely discussed by the literature related to Internet of Thinfs (IoT) applications in the energy field, especially to find out protocols and tools to overcome the privacy loss risk. The environment we are looking at is "open and decentralized" and security and privacy shall be guaranteed by proper tools [Copos et al., 2016]. A similar approach can be found in Kianmajd et al. [2016]. Le Cadre and Bedo [2020] study the problem of interaction of consumers and prosumers on the exchange platform, also considering the privacy preservation by a consensus algorithm. As EC are relatively recent, and there are not many data coming from applications, it is more frequent to find studies concerning privacy issues relatively to the installation of smart meters, for which it is possible to create samples and questionnaires [Schallehn and Valogianni, 2022, Hmielowski et al., 2019]. In this work, we account for privacy costs in the framework developed by Choi et al. [2019]: the authors consider the role of personal information in determining market equilibrium in a monopoly. The theoretical framework highlights the presence of externalities that determine coordination failures. Our work will extend the literature regarding this aspect as, together with the environmental benefit potentially represented by the establishment of EC and the consequent optimization of consumption, we will consider the presence of externalities that can determine costs (private and social) deriving from the information flows that are used in these contexts.

This approach moves from the observation that data collected from individuals might have multiple uses nowadays.[4]

The paper is organized as follows: Section 2 provides an overview on the general framework, Section 3 describes our theoretical model, Section 4 introduces the further scenario dealing with a social optimum perspective, Section 5 shows a brief comparison between the outcome of the two scenarios and Section 6 concludes.

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[4] For further discussion on the side see Bergemann et al. [2020].

2 Basic set up

We consider a municipality (M/he), that is willing to pay the cost of establishing a REC [5]. The overall required investment cost consists of RE plants, storage facilities and connections to the local grid.[6]

The municipality is assumed to be benevolent and utilitarian, in the sense that it maximizes the sum of the expected present value of the inter-temporal utility of the REC members determining the optimal investment timing.

The management of the REC is entrusted by M to an Aggregator (A/she), operating as profit-maximizer, providing all the ICT infrastructure needed from the REC members to optimize their energy consumption (SG, smart grid) as well as selling to the community the additional energy needed to cover the members' energy demand that cannot be satisfied with the REC's inner production.[7] A chooses the optimal REC's size and sets the price for the energy sold to the REC's members (p). In addition A, through the SG, is able to collect a certain detail of information concerning the members' energy consumption behaviors across energy devices and related timing. This information is sold by A to - for instance - consumers' products (CP) firms, generating a flow of extra revenues. Finally, the municipality pays a fixed tariff per member and per period (w) to A for the REC's management.

The members of the REC are heterogeneous in the assessment of the overall service provided by the REC. They decide to engage in it if their valuation (x) is high enough: this reflects, de facto, their willingness to sign the contract with A for the residual energy demand that cannot be satisfied by REC's production. Thus, the utility of each agent is function of such valuation x, the price p and accounts also for the privacy cost arising from the aggregator data collection policy.[8] The conceptual framework of the model is presented in Figure 1.

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[5] At the time of writing, this setup is quite frequent in the pilot ECs activation.

[6] All additional works needed to connect power plants and storage facilities to the network are part of the investment. No additional network lines are built, as the REC uses the existing distribution network to exchange energy.

[7] In our setup, A is not producing energy, but serve as intermediary between the community and other energy producers.

[8] In this work we do not deal with the criteria of how sharing benefits among the members of the REC, thus in our model the agents are treated symmetrically.

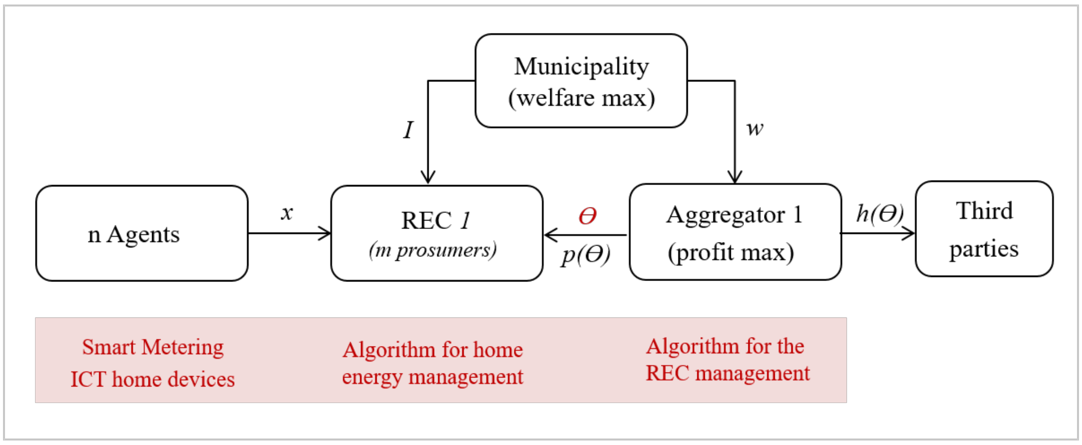

Figure 1: Model chart

2.1 Main assumptions

In what follows, we summarize main assumptions of our model. Lets start considering the potential REC members. There is a mass one of agents which are all energy users. Each agent i has his/her own valuation of the SG service provided by A, which we denote as $x \in [\underline{x}, \bar{x}]$, with distribution F and density f. We assume that F satisfies the standard monotone hazard rate condition, that is, $\frac{f}{1-F}$ is non-decreasing in x, while $f(\underline{x}) > 0$ and $f(\bar{x}) > 0$.
The dimension of the REC depends on the valuation x each agent has for the SG service. If we define as m, the mass of agents that join the REC, this will be given by:

$$m = 1 - F(x), \tag{1}$$

where x is the cutoff type such that all agents, whose valuation exceeds or it is equal to x, join the REC. If $x = \underline{x}$ then $m = 1$. That is, if x is sufficiently high, respect to the lower bound $\underline{x}$, the REC is "fully covered".

The agents are heterogeneous in valuating the service provided by the REC and they are symmetric on the side of the energy demand. Considering the typology of agents in the model (residential consumers), their share a similar pattern but peak loads might occur in different hour of the day.
The level of agents' energy demand, which we denote as k_i, is instead the same for all potential REC participants, thus $k_i = k$.[9] They can satisfy their energy demand self-consuming the energy produced from

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[9] Considering, for example, a day (i.e., 24 hours) as a unitary measure of time, $k_i \equiv \int_0^{24} l(s)ds$ where $l(s)$ denotes the consumption of energy at time $s \in [0, 24]$.

RE plants as well as sourcing it through the exchange P2P within the REC. The residual demand is then satisfied purchasing energy from A at price p. [10] Denoting with k the per-period demand of energy, this is equal to:

$$k = \text{energy purchased} + \sigma\left(m\right), \tag{2}$$

where $\sigma\left(m\right)$ is the energy self-consumed and exchanged within the REC, as a function of the number of members of the REC. We require $\sigma\left(m\right)$ to be an increasing and convex function of m, with properties: $\sigma\left(0\right) < \sigma(1) < k$ and $\sigma'(0) > 0$. When $m = 0$ the agents satisfy their energy demands on their own. We denote such a case with $\sigma\left(0\right)$, representing the mere self-consumption scenario. On the other hand $\sigma(1) < k$, implying that even if the REC is "fully covered", the agents' energy demand cannot be completely satisfied by the REC production.[11]

Finally, we introduce the following assumption on the side of the aggregator. For managing the REC, A uses an ICT infrastructure composed of a P2P platform. The interaction of this software with the agents' home smart devices allows the efficient management of the renewable energy consumption, as well as the collection of information regarding the energy behaviors of the REC's members. [12] If on one side, this information is a fundamental part of the SG service for increasing energy consumption efficiency, on the other it also allows the understanding of the prosumers' sensitivity respect the use of renewable energy together with their use of energy devices across types and time.

We measure the rank of detail of this information through the variable θ distributed over the interval $[0, 1]$, with distribution function G and density g. A high value of θ means that very "private" information is collected,[13] on the contrary a low θ means that A learns only "basic" information. A may decide to collect all types of information over the range from 0 to a certain level $\hat{\theta} \leq 1$.

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[10] On this side we follow the same demand structure presented in Castellini et al. [2021]

[11] The members of the REC can satisfy their energy demand self consuming the energy produced from RE plants, which we can define $\xi\left(m\right)$, as well as sourcing it through the exchange P2P within the REC, namely $\gamma\left(m\right)$. Both ξ and γ turns out to be functions of the number members m, the REC size. While it is likely that $\xi'(m) < 0$, since the higher is m, the RE plant size associated to each agent decreases together with the self consumption level [Andreolli et al., 2022], the exchange P2P γ increases with m. When $m = 0$, each agent consumes autonomously, with no energy exchange and with a self-consumed energy that is a quota of the overall plant production.
The higher the number of participants to the REC, the higher the efficiency of the single load, meaning that REC members satisfy better their energy needs, thanks to the exchange P2P. In other words, an increase in m leads an improvement in different load curves matching, such that the net effect of an increase in the community size, represented by $\sigma\left(m\right) = \xi\left(m\right) + \gamma\left(m\right)$, is positive and convex.

[12] Our ideal framework is the one where members of the REC are endowed with smart energy metering system combined with an algorithm for home energy management. This ICT context allows the collection of information on RE self consumption and exchange P2P together with private information about the activity of each home energy device connected to this software. Of course, this is needed so that efficient RE consumption and optimal REC operation are achieved.

[13] Such as instantaneous energy consumption, details across devices types and timing.

The measure of the information collected is given by:

$$h(\hat{\theta}) = \int_0^{\hat{\theta}} dG(\theta). \tag{3}$$

Each agent associates a certain cost to the information collection undertaken by A, which can be interpreted as an increasing risk of data breach accidents and/or perceived negative effects connected to personal privacy loss.[14]

For the sake of brevity we will also refer to this as "privacy cost" and denote it, for a given category of information θ, as $\psi(\theta)$. We assume that $\psi(\theta)$ is characterized by the following properties $\psi'(\theta) > 0, \psi''(\theta) \geq 0$ and $\psi(0) = 0$.[15] If A decides to collect a set of information that ranges over the interval $\left[0, \hat{\theta}\right]$, the total privacy cost incurred by the members of the REC per unit of time becomes: [16]

$$\Psi(\hat{\theta}) = \int_0^{\hat{\theta}} \psi(\theta) dG(\theta). \tag{4}$$

As we said, the information collected within the REC can be used by A either to sell other services to the members, both RES-related and not,[17] or sell it "raw"directly to third parties, such as to consumers' product (CP) firms.[18] On this basis, we define as $R\left(h\left(\hat{\theta}\right), m\right)$ the per period additional revenues that A can obtain thanks to the data gathered from the members of the REC. Specifically, we assume that:

$$R\left(h\left(\hat{\theta}\right), m\right) = m\rho\left(h\left(\hat{\theta}\right)\right), \tag{5}$$

and to be increasing in both h and m and concave in h.

The REC creation requires a sunk investment of I per member. We assume the investment cost to be stochastic and evolving overtime according a Geometric Brownian Motion (GBM, hereafter):

$$dI_t = \mu I_t dt + \eta_t dB_t \quad \text{with} \quad I_{t=0} = I_0, \tag{6}$$

with drift rate μ, volatility rate η and dB_t the increment of the standard Wiener's process, satisfying

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[14] See Choi et al. [2019] for various justifications and literature on privacy cost.

[15] In other words the cost of a "basic" information ($\theta \to 0$) is nil, while the "private"information cost ($\theta \to 1$) is high.

[16] Following Choi et al. [2019] the privacy cost $\Psi\left(\hat{\theta}\right)$ can be interpreted as the net cost, after subtracting any benefit each REC member can gain from sharing information with A

[17] For instance offering home automation services for energy saving but also home appliances or electric bikes or cars.

[18] See discussion on this side provided by Bergemann et al. [2020],among others.

$\mathbb{E}\left[dB_t\right]=0$ and $\mathbb{E}\left[dB_t^2\right]=dt$.

Armed with the above assumption, the per-period function of each member's utility can be written as:

$$u(m)=(x-p)\left(k-\sigma\left(m\right)\right)-\Psi\left(\hat{\theta}\right), \tag{7}$$

where p is the price of energy set by A, $k-\sigma\left(m\right)$ is the energy purchased and $\Psi\left(\hat{\theta}\right)$ the privacy cost.[19] The per-period profit function of the aggregator is:

$$\pi(m)=mp\left(k-\sigma\left(m\right)\right)+mw+R\left(h,m\right), \tag{8}$$

where the term $mp\left(k-\sigma\left(m\right)\right)$ represents the revenue obtained from the sell of energy to the members of the REC, mw is payment received from the municipality and $R\left(h,m\right)$ the extra revenues gathered thanks to the information collected within the REC.

Finally, denoting with τ the time the REC is created and with mI_τ the level of REC's overall cost at that moment, the objective function to be optimized at time $t=0$ by the municipality can be written as follows:

$$W\left(m\right)=\left(\frac{I_0}{I_\tau}\right)^{\beta}\left[\frac{U\left(m\right)}{r}-m\left(\frac{w}{r}+I_\tau\right)\right], \tag{9}$$

where $U\left(m\right)$ and w are the per-period utility of the REC and the payment to A respectively, r the discount rate and $\left(\frac{I_0}{I_\tau}\right)^{\beta}=E_0(e^{-r\tau})$ is the "expected discount factor" with $\beta<0$ as the negative root of the characteristic equation $\Psi\left(y\right)=(\sigma^2/2)y\left(y-1\right)+\mu y-r$ [Dixit and Pindyck, 1994].

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[19] For simplicity we assume that the energy received and exchanged within the REC balances for each member.

3 The model

The model is set in continuous time with an infinite horizon and it is assumed M acting in the interest of REC's members. The sequence of events and decisions is as follows.

At time $t = 0$, the municipality M bargains with the aggregator A concerning the REC management cost w. Such cost remains the same along all the time period in which A manages the REC.[20] Once w is given, M evaluates the optimal time τ to set up the REC.

At time $t = \tau$, the REC is created and the aggregator sets the price p of the energy needed to cover the share of REC's members energy demand which is not satisfied through its inner production. As A is aware that participation in the REC is voluntary and based on the valuation x, the choice of the price implicitly determines the REC size.

Working backward, we proceed by solving first the aggregator's maximization problem and then turning to the municipality investment problem.

Once the REC is active, the aggregator's optimization problem can be thus written in the following way:

$$\begin{aligned}&\max_{p} \int_0^{\infty} e^{-rt}\pi(m)dt \\ &\text{s.t.} \quad u(m) \geq \bar{u} \quad \text{for all} \quad t \geq 0,\end{aligned} \tag{10}$$

where $\bar{u}$ indicates the per-period reservation utility. Since each agent is free to leave the REC anytime, he/she will meet the entire demand k with a standard contract.[21] We assume that the cost of the standard contract is such that $\bar{u} = 0$.

Thus, letting x be the cutoff type of agent who is indifferent between being part of the REC or not, the price p such the Individual Rationality (IR) constraint is binding is:

$$p = x - \frac{\Psi\left(\hat{\theta}\right)}{\left[k - \sigma\left(m\right)\right]}. \tag{11}$$

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[20] see Appendix A for further details.

[21] Undersigned with an energy provider, but without any SG service.

Substituting p and $m = 1 - F(x)$ in Eq. (10), A solves:

$$\max_{x} r\pi(x) \tag{12}$$

$$\text{where} \qquad \pi(x) = [1 - F(x)] \left[x\left(k - \sigma\left(1 - F(x)\right)\right) + w - \Psi(\hat{\theta}) \right] + R\left(h, 1 - F(x)\right). \tag{13}$$

Denoting with x^M the profit-maximizing optimal cutoff, this is given by (see Appendix B):

$$\underbrace{\left(x^M - \frac{1 - F\left(x^M\right)}{f(x^M)} \right) \left(k - \sigma\left(1 - F\left(x^M\right)\right)\right) + \ w +}_{\text{Virtual valuation}} \underbrace{\frac{\partial R}{\partial m}}_{\text{Aggregator Marginal revenue}}$$
$$= \underbrace{\left[1 - F\left(x^M\right)\right] x^M \sigma'\left(1 - F\left(x^M\right)\right) + \Psi\left(\hat{\theta}\right).}_{\text{Aggregator Marginal Cost}} \tag{14}$$

The LHS of Eq. (14) is composed of two elements: i) the virtual valuation of the agent, i.e. $x^M - \frac{1-F\left(x^M\right)}{f(x^M)}$, respect to the energy purchased from A, namely $k - \sigma\left(1 - F\left(x^M\right)\right)$, which in turn depends on the overall self consumption of renewable energy of the REC, ii) the fee A receives from M and iii) the marginal revenue gained from the sell of the additional services or the information collected it selves to third parties.
The RHS is the aggregator marginal cost arising from the collection of data of the additional agent, which in turn depends on the size of the REC, $m^M = 1 - F\left(x^M\right)$, and the cost associated to agent's privacy loss $\Psi\left(\hat{\theta}\right)$. From (14) we can prove the following proposition.

Proposition 1 *The aggregator marginal cost is non increasing in $\hat{\theta}$, the higher is the detail of the information collected by the aggregator the lower is the REC size:*

$$\frac{dx^M}{d\hat{\theta}} > 0 \rightarrow \frac{dm^M}{d\hat{\theta}} < 0. \tag{15}$$

Conversely, an increase on the side of the fee w leads to an higher REC size:

$$\frac{dx^M}{dw} < 0 \rightarrow \frac{dm^M}{dw} > 0. \tag{16}$$

The complete Proof is provided in Appendix C.

By Substituting then $m^M = 1 - F\left(x^M\right)$ in (7) and (11) we obtain the per-period utility of the REC as:

$$\begin{aligned} U(x^M) &= \int_{x^M}^{\bar{x}} u(x, x^M) dF\left(x\right) && (17) \\ &= \left[k - \sigma\left(1 - F\left(x^M\right)\right)\right] \left[\left(\bar{x} - x^M\right) - \int_{x^M}^{\bar{x}} F\left(x\right) dx\right], && (18) \end{aligned}$$

where the per-period utility of each member of the REC is:

$$u\left(x, x^M\right) = \left(x - x^M\right) \left[k - \sigma\left(1 - F\left(x^M\right)\right)\right] \geq 0 \qquad \text{for all } x \in \left[x^M, \bar{x}\right]. \tag{19}$$

Note that when the optimal cut off is $x^M = \bar{x}$, then $m^M = 0$ and $U(\bar{x}) = 0$. On the contrary when $x^M = \underline{x}$, then $m = 1$ and $U\left(\underline{x}\right) = \left(\mathbb{E}(x) - \underline{x}\right)\left(k - \sigma\left(1\right)\right) > 0$.

Now, let us consider a further issue to make our analysis more interesting. We now assume that the heterogeneity of the members of the REC is such that the elasticity of the energy demand with respect to the size of the REC is not too high, i.e.:

$$\frac{\sigma'\left(1\right) f\left(\underline{x}\right) \underline{x}}{k - \sigma\left(1\right)} < \frac{\underline{x}}{x - \underline{x}} \qquad \text{for all} \quad x \in \left[\underline{x}, \bar{x}\right]. \tag{20}$$

This new assumption is consistent with reality, since an increase in the REC size leads to a shifting in the agents' RE consumption from a 50% of the overall RE production, in the case of the mere self-consumption scenario ($\sigma\left(0\right)$), to a maximum level of 80% when the REC is fully covered ($\sigma\left(1\right)$).[22] In other words, the REC increases the consumption of RE of 30%. Thus, under this new consideration, the REC utility is always increasing in the size of the REC (see Appendix C):

$$\begin{aligned} \frac{\partial U\left(x^M\right)}{\partial x^M} &= -\int_{x^M}^{\bar{x}} \frac{\partial u\left(x, x^M\right)}{\partial x^M} dF\left(x\right) < 0 && (21) \\ &= \sigma'\left(1 - F\left(x^M\right)\right) f(x^M) \left(\left(\bar{x} - x^M\right) - \int_{x^M}^{\bar{x}} F\left(x\right) dx\right) - \left(k - \sigma\left(1 - F\left(x^M\right)\right)\right)\left(1 - F\left(x^M\right)\right) < 0, \\ &\text{with} \quad \frac{\partial U\left(x^M\right)}{\partial x^m}\Big|_{x^M = \bar{x}} = 0 \quad \text{and} \quad \frac{\partial U\left(x^M\right)}{\partial x^m}\Big|_{x^M = \underline{x}} = 0. && (22) \end{aligned}$$

---

[22] In this last scenario, the self-consumption of RE is combined with exchange P2P possibility.

Finally, the municipality's optimization problem can be written as follows:

$$\max_{I_\tau} rW(m) \qquad \text{where:} \tag{23}$$
$$W(m) = \left(\frac{I_0}{I_\tau}\right)^{\beta}\left[\left(k-\sigma\left(1-F\left(x^M\right)\right)\right)\left(\left(\bar{x}-x^M\right)-\int_{x^M}^{\bar{x}}F(x)\,dx\right)-\left(1-F\left(x^M\right)\right)\left(w+rI_\tau\right)\right].$$

Denoting then with I^M the welfare-maximizing investment cost, this is given by:

$$\begin{aligned} rI^M &= \frac{\beta}{\beta-1}\frac{\left(k-\sigma\left(1-F\left(x^M\right)\right)\right)\left(\left(\bar{x}-x^M\right)-\int_{x^M}^{\bar{x}}F(x)\,dx\right)}{1-F\left(x^M\right)}-\frac{\beta}{\beta-1}w \\ &= \frac{\beta}{\beta-1}\frac{U\left(m^M\right)}{m^M}-\frac{\beta}{\beta-1}w \end{aligned} \tag{24}$$

together with the optimal expected investment time $\mathbb{E}_0[\tau]$ (see appendix D):

$$\mathbb{E}_0[\tau] = I^M - I_0 - \frac{\mu}{2}e^{\left(2\mu+2\eta^2\right)}. \tag{25}$$

Note that the optimal investment trigger I^M is driven, mainly, by average utility, i.e.$\frac{U(m)}{m}$. Since an increase of the size of the REC highers both the numerator and the denominator, it is not known whether this involves an acceleration of the investment or a delay. Some insights can be provided by the study of the derivative, provided in Appendix D.

We conclude the section, with the aggregator's data collection policy. Given the measure of the network m, the aggregator's optimal type for data collection $\hat{\theta}$ can be characterized by:[23]

$$\begin{aligned} \frac{\partial\pi(x)}{\partial\hat{\theta}} &= \frac{\partial\rho}{\partial h}g(\hat{\theta})-[1-F(x)]\,\psi(\hat{\theta})g(\hat{\theta})=0 \\ &= \frac{\partial\rho}{\partial h}-[1-F(x)]\,\psi(\hat{\theta})=0. \end{aligned} \tag{26}$$

Since the aggregators' revenues are increasing respect to the information collected, thus $\frac{\partial\rho}{\partial h}>0$, while the higher is the size of the REC, the bigger is the negative effect induced by the agents privacy cost, the type for data collection $\hat{\theta}$ maximizing the aggregator's profit is affected by three main driving forces: its revenues gained from the sell of information, the size of the REC, affect by the agents' valuation x and the privacy cost perceived by the agents respect to the data collection type $\hat{\theta}$

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[23] The SOC is always satisfied.

4 A social optimum scenario

We now analyze the socially optimal outcome as a benchmark in which the municipality decides to conduct the REC itself.[24] Under this scenario, we separate our problem in two steps. Working backward, once the REC is active, the municipality's optimization problem to determine the social cutoff type is:

$$\max_{x} rV(x)$$
$$\text{with} \qquad V(x) = \int_{x}^{\bar{x}} x(k-\sigma(1-F(y)))dF(x) + R(h(\hat{\theta}), 1-F(x)) - [1-F(x)]\Psi(\hat{\theta}). \tag{27}$$

with $V(x)$ being the per-period social value and the control the agents' REC valuation.
Denoting with x^W the optimal cutoff under this scenario, this is given by:

$$\underbrace{x^W(k-\sigma(1-F(x^W)))}_{\text{Valuation}} + \underbrace{\frac{\partial R}{\partial m}}_{\text{Marginal revenue}} = \underbrace{\Psi(\hat{\theta})}_{\text{Social Marginal Cost of an additional member}}. \tag{28}$$

From Eq. (28), we can prove that:

Proposition 2 *The higher is the detail of the information collected by the municipality the lower is the REC size:*

$$\frac{dx^W}{d\hat{\theta}} > 0 \rightarrow \frac{dm^W}{d\hat{\theta}} < 0. \tag{29}$$

Then the municipality's optimization problem reduces in the identification of the investment cost which makes it socially viable to activate the REC, i.e.:

$$\max_{I_\tau} rW\left(x^W\right)$$
$$\text{where} \qquad W\left(x^W\right) = \left(\frac{I_0}{I_\tau}\right)^{\beta}\left[V(x^W) - \left(1-F\left(x^W\right)\right)(rI_\tau)\right] \tag{30}$$

---

[24] We can imagine a scenario in which M entrusts a public utility company of his ownership or a inner technical team of its employees.

Denoting with I^W the welfare-maximizing investment under this social optimum scenario, this is given by:

$$\begin{aligned} rI^W &= \frac{\beta}{\beta-1}\frac{\int_{x^W}^{\bar{x}} y(k-\sigma(1-F(y)))dF(y) + R(h(\hat{\theta}), 1-F(x^W))}{1-F\left(x^W\right)} - \frac{\beta}{\beta-1}(\Psi(\hat{\theta}) \qquad (31) \\ &= \frac{\beta}{\beta-1}\frac{V(m^W)-m^W\Psi(\hat{\theta})}{m^W} \end{aligned}$$

where the last expression comes from $m^W = 1-F(x^W)$. The term $V(m^W) - m^W\Psi(\hat{\theta})$ represents the difference between the per-period social value of the REC and the overall privacy cost, that is: [25]

$$V(m^W) - m^W\Psi(\hat{\theta}) = U(m^W) + \int_{x^W}^{\bar{x}} x[\sigma(1-F(x^W)) - \sigma(1-F(x)))]dF(x), \qquad (32)$$

where the second term on the R.H.S. of (32) is positive. Substituting (32) in (31) we obtain:

$$rI^W = \frac{\beta}{\beta-1}\frac{U(m^W)}{m^W} + \frac{\beta}{\beta-1}\frac{\int_{x^W}^{\bar{x}} x[\sigma(1-F(x^W)) - \sigma(1-F(x)))]dF(x)}{m^W} \qquad (33)$$

Again we conclude with the data collection policy carried out now by the municipality. Once the dimension of the REC is determined, the optimal data collection $\hat{\theta}$ can be characterized by:

$$\begin{aligned} \frac{\partial V(x)}{\partial\hat{\theta}} &= \frac{\partial\rho}{\partial h}g(\hat{\theta}) - [1-F(x)]\psi(\hat{\theta})g(\hat{\theta}) = 0 \qquad (34) \\ &= \frac{\partial\rho}{\partial h} - [1-F(x)]\psi(\hat{\theta}) = 0 \qquad \text{for } g(\hat{\theta}) > 0 \end{aligned}$$

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[25] See Appendix E for further details.

5 Comparison and discussion

The following proposition yields from the comparison of Eq. (14) and (28).

Proposition 3 *For any given $\hat{\theta} > 0$, the optimal dimension of the REC identified by the aggregator is always smaller than the optimal one decided by the municipality. i.e.:*

$$x^M > x^W \to m^M < m^W \tag{35}$$

In addition, the self-consumption with a REC managed by the aggregator is lower:

$$\sigma\left(m^M\right) < \sigma\left(m^W\right) \tag{36}$$

In addition, from Eq. (26) and (34), we obtain that the level of information collected is:

Proposition 4 *For any given value of the cutoff x*

$$\hat{\theta}^M(x) = \hat{\theta}^W(x) = \hat{\theta}^*(x) \tag{37}$$

$$\textit{with the property} \qquad \frac{\partial \hat{\theta}^*}{\partial x} > 0 \tag{38}$$

The proof is provided in Appendix F.

The aggregator optimal REC size is smaller than the socially optimal one. Information collection is more intensive if the REC operation is entrusted by the municipality to the aggregator. Finally, from Eq. (24) and (33) we may conclude that:

Proposition 5 *For any given $\hat{\theta}$, the municipality invest earlier if it also manage the REC operation.*

$$I^W > I^M.$$

6 Conclusions

The paper discusses the role of private information costs on determining the willingness of agents to participate to a REC. Considering the targets of the potential participants, of the aggregator A and of the promoter, which is in our case the municipality M, it is possible to identify the optimal size of the REC and the optimal investment time.

In the discussion, we decided to highlight the role of private information as an additional cost to be considered in the evaluation of the REC initiative: this component is often missing in their valuation, since many authors mainly focused on other aspects such as energy savings, CO2 savings and preferences towards environmental sustainability. As in many other sector and "free" services, however, the transfer of personal data seems to be a relevant cost to be paid. Privacy costs in our work are connected to the use of information for marketing purposes: it is evident that the use of information to modulate the price of energy represents another relevant component for the evaluation of the costs of privacy. It is worth to specify that information regarding private habits on energy loads are heavily relevant in the energy market: energy providers would take an heavy (and unbalanced) advantage knowing this kind of data. This component in the work is discussed in the trade-off of the aggregator, which makes a profit from the sale of energy when EC management performance is lower.

Future extensions of the work should consider differences among consumers, giving a value to different attitudes in sharing personal information, also linking them to concepts like energy access and energy poverty. Costs and benefit sharing are not modelled on the agents' characteristics, while other works do. These approaches contribute to a rigorous discussion about the promotion and the establishment of the energy communities, beyond ideological positions.

In a model where a single agent (for us, the aggregator) has the power to both manage the energy community to maximize self-consumption and to sell additional energy when necessary, the role of information is much relevant also keeping the discussion only inside the energy market. The condition of A immediately leads to a trade-off between the EC performance (i.e. high levels of self-consumption) and the potential revenues deriving from the activity of energy selling. This aspect is exacerbated by the role played by private information on consumes, which is the aspect we want to analyse as a major issue in the decentralization of energy system management. Similar criticalities are the basis for the unbundling regulation that impede to the network manager (DSOs) to be also active in the energy markets as sellers.

Further research shall go deeper in the effects that the use of private information on consumes might determine in the new local energy markets, where different roles and limits for the new agents still need to be discussed.

Moreover, the role of the aggregator shall be further outlined by considering its role in the relationship with the local DSO. Indeed, EC shall work to minimize system costs, and this aspect can be translated into an agreement/contract between the aggregator and the local DSO in terms of shared benefits or, vice versa, penalties in case of deviation e.g. from an agreed load pattern. In this work we are not considering this aspect, assuming that the EC is established properly in the network and it is efficiently integrated, but further researches will complete the scheme to better identify the relationship between the EC and the network.

Another relevant feature of the setup is the choice of the municipality as EC promoter: this approach is linked to the literature of PPPs and the investments for the energy transition. Since the development of EC is still in a preliminary phase, pilot experiences are arising thanks to municipalities or local authorities: this evidence gives the opportunity to study how to establish new contracts between public and private agents, which kind of conditions are necessary to make the contract efficient, and how to regulate them.

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Appendix A - Bargaining between the municipality and the aggregator.

If M and A agree on the fee, for each period of time they will gain respectively $-mw$ and mw. Otherwise, in the non cooperative scenario, they will get $-mw^h$ and mw^l, where w^l is the lower fee level the municipality is willing to pay and w^h is the one for which the municipality pays all the REC's management cost.

The outcome of the negotiation is the solution of the following optimization problem:

$$\max\left[(mw - mw^l)^{\alpha}(-mw + mw^h)^{1-\alpha}\right] \tag{A.1}$$

where $\alpha \in [0, 1]$ is the municipality bargain power.

The resolution of the following first order condition yields the agreed fee for the REC operation.

$$\begin{aligned}
&\alpha(mw - mw^l)^{\alpha-1}m(-mw + mw^h)^{1-\alpha} + (mw - mw^l)^{\alpha}(1-\alpha)(-mw + mw^h)^{-\alpha}(-m) = 0\\
&m(mw - mw^l)^{\alpha}(-mw + mw^h)^{1-\alpha}[\alpha(mw - mw^l)^{-1} - (1-\alpha)(-mw + mw^h)^{-1}] = 0\\
&\alpha(mw - mw^l)^{-1} - (1-\alpha)(-mw + mw^h)^{-1} = 0\\
&\alpha(-mw + mw^h) = (1-\alpha)(mw - mw^l)\\
&-\alpha w + \alpha w^h = (1-\alpha)w - (1-\alpha)w^l\\
&-\alpha w - (1-\alpha)w = -(1-\alpha)w^l - \alpha w^h\\
&w = (1-\alpha)w^l + \alpha w^h \qquad \text{(A.2)}
\end{aligned}$$

where, if $w^l = 0$, we obtain $w = \alpha w^h$.

Appendix B - The aggregator profit maximization

The first order condition.

$$\frac{\partial \pi\left(x,\hat{\theta}\right)}{\partial x}=0 \tag{B.1}$$

$$\begin{aligned}&-f(x)\left[x(k-\sigma(1-F(x)))+(w-\Psi(\hat{\theta}))\right]+\\&[1-F(x)]\left[(k-\sigma(1-F(x)))+x(-\sigma'(1-F(x))(-f)\right]+\frac{\partial R}{\partial m}(-f)=0\end{aligned}$$

$$\begin{aligned}&-\left[x(k-\sigma(1-F(x)))+(w-\Psi(\hat{\theta}))\right]+\\&\frac{[1-F(x)]}{f(x)}\left[k-\sigma(1-F(x))+x\sigma'(1-F(x))f(x)\right]-\frac{\partial R}{\partial m}=0\end{aligned}$$

$$\begin{aligned}&-xk+x\sigma(1-F(x))-w+\frac{[1-F(x)]}{f(x)}k-\\&\frac{[1-F(x)]}{f(x)}\sigma(1-F(x))+[1-F(x)]x\sigma'(1-F(x))-\frac{\partial R}{\partial m}=-\Psi(\hat{\theta})\end{aligned}$$

$$-(x-\frac{[1-F(x)]}{f(x)})(k-\sigma(1-F(x)))-\frac{\partial R}{\partial m}+[1-F(x)]x\sigma'(1-F(x))=(w-\Psi(\hat{\theta}))$$

$$(x-\frac{[1-F(x)]}{f(x)})(k-\sigma(1-F(x)))+w+\frac{\partial R}{\partial m}=[1-F(x)]x\sigma'(1-F(x))+\Psi(\hat{\theta})$$

$$\begin{aligned}&\underbrace{\left(x-\frac{1-F\left(x\right)}{f(x)}\right)\left(k-\sigma\left(1-F\left(x\right)\right)\right)}_{\text{Virtual valuation}}+\ w+\quad\underbrace{\frac{\partial R}{\partial m}}_{\text{Marginal revenue}}\\&=\qquad\underbrace{\left[1-F\left(x\right)\right]x\sigma'\left(1-F\left(x\right)\right)+\Psi\left(\hat{\theta}\right)}_{\text{Private Marginal Cost from data collection of additional prosumer}}\end{aligned} \tag{B.2}$$

The second order condition.

$$\frac{\partial^2 \pi \left(x, \hat{\theta}\right)}{\partial^2 x} = 0 \tag{B.3}$$

$$\begin{aligned}
&-\frac{d}{dx}(x - \frac{[1 - F(x)]}{f(x)})\frac{(k - \sigma(1 - F(x)))}{f} - (x - \frac{[1 - F(x)]}{f(x)})(\sigma'(1 - F(x)) \\
&+\frac{\partial^2 R}{\partial m^2} - \sigma'(1 - F(x))\left(x - \frac{[1 - F(x)]}{f}\right) - x\sigma''(1 - F(x))(f)\frac{[1 - F(x)]}{f} < 0
\end{aligned} \tag{B.4}$$

where sufficient, not necessary, condition is $x - \frac{[1-F(x)]}{f(x)} > 0$, meaning that the virtual valuation must be always positive.

Appendix C - Proof of proposition 1.

Recalling that

$$u\left(x, x^M\right) = \left(x - x^M\right)\left(k - \sigma\left(1 - F\left(x^M\right)\right)\right) \qquad \text{for all } x \in \left[x^M, \bar{x}\right] \tag{C.1}$$

taking the derivative with respect to x^M we get:

$$\frac{\partial u\left(x, x^M\right)}{\partial x^M} = -\left(k - \sigma\left(1 - F\left(x^M\right)\right)\right) + \left(x - x^M\right)\sigma'\left(1 - F\left(x^M\right)\right) f\left(x^M\right). \tag{C.2}$$

Thus $\frac{\partial u\left(x, x^M\right)}{\partial x^M} < 0$ if :

$$\frac{\sigma'\left(1 - F\left(x^M\right)\right) f\left(x^M\right)}{\left(k - \sigma\left(1 - F\left(x^M\right)\right)\right)}\left(x - x^M\right) < 1.$$

Note that when the cut off is $x^M \to \bar{x}$, i.e. $m = 0$ we get $\frac{\sigma'(0) f(\bar{x})}{(k - \sigma(0))}(0) = 0$, while when $x^M \to \underline{\mathrm{x}}$, i.e. $m = 1$, we obtain:

$$\frac{\sigma'(1) f(\underline{\mathrm{x}})}{(k - \sigma(1))}(x - \underline{\mathrm{x}}),$$

which is the expression in the text.

Considering then the further assumption for which heterogeneity of the members of the REC is such that the elasticity of the energy demand with respect to the size of the REC is not too high we obtain:

$$\begin{aligned}
\frac{\partial U\left(x^M\right)}{\partial x^M} &= \sigma'\left(1 - F\left(x^M\right)\right) f(x^M)\left(\left(\bar{x} - x^M\right) - \int_{x^M}^{\bar{x}} F(x)\, dx\right) \\
&\quad -(k - \sigma\left(1 - F\left(x^M\right)\right))\left(1 - F\left(x^M\right)\right), && \text{(C.3)}
\end{aligned}$$

with

$$\frac{\partial U\left(x^M\right)}{\partial x^M}\Big|_{x^M = \bar{x}} = \sigma'(0) f(\bar{x})(0) - (k - \sigma(0))(0) = 0, \tag{C.4}$$

$$\frac{\partial U\left(x^M\right)}{\partial x^M}\Big|_{x^M = \underline{\mathrm{x}}} = \sigma'(1) f(\underline{\mathrm{x}})(E(x) - \underline{\mathrm{x}}) - (k - \sigma(1)) < 0, \tag{C.5}$$

and

$$
\begin{aligned}
\frac{\partial^2 U\left(x^M\right)}{\partial (x^M)^2} &= \sigma''\left(1-F\left(x^M\right)\right) f(x^M)\left(\left(\bar{x}-x^M\right)-\int_{x^M}^{\bar{x}} F\left(x\right)dx\right) \qquad \text{(C.6)}\\
&\quad +\sigma'\left(1-F\left(x^M\right)\right) f'(x^M)\left(\left(\bar{x}-x^M\right)-\int_{x^M}^{\bar{x}} F\left(x\right)dx\right)+\\
&\quad -\sigma'\left(1-F\left(x^M\right)\right) f(x^M)(1-F\left(x^M\right)) - \sigma'\left(1-F\left(x^M\right)\right) f(x^M)\left(1-F\left(x^M\right)\right)\\
&\quad +(k-\sigma\left(1-F\left(x^M\right)\right))f(x^M)\\
&= \sigma''\left(1-F\left(x^M\right)\right) f(x^M)\left(\left(\bar{x}-x^M\right)-\int_{x^M}^{\bar{x}} F\left(x\right)dx\right)+\\
&\quad +\left(1-F\left(x^M\right)\right)\frac{f(x^M)}{(1-F\left(x^M\right))}\left(\sigma'\left(1-F\left(x^M\right)\right)\left(\left(\bar{x}-x^M\right)-\int_{x^M}^{\bar{x}} F\left(x\right)dx\right)\right)\\
&\quad -\left(1-F\left(x^M\right)\right)\left(k-\sigma\left(1-F\left(x^M\right)\right)\right)
\end{aligned}
\qquad \text{(C.7)}
$$

Appendix D - The optimal investment

The optimal trigger. Let consider first the case where $x^M = \bar{x}$, i.e. $m = 0$. In this case taking the limit of (24), we are able to proof that:

$$\lim_{x^M \to \bar{x}} rI^M = -\frac{\beta}{\beta - 1} w. \tag{D.1}$$

On the contrary:

$$\lim_{x^M \to \underline{\mathrm{x}}} rI^M = \frac{\beta}{\beta - 1} U\left(\underline{\mathrm{x}}\right) - \frac{\beta}{\beta - 1} w. \tag{D.2}$$

When m is too low, the REC investment it is never convenient for M. While if the REC is fully covered, the optimal time is given by $\frac{\beta}{\beta-1} U\left(\underline{\mathrm{x}}\right) - \frac{\beta}{\beta-1} w$.

Taking the derivative of (24) with respect to x^M we get:

$$\frac{\partial rI^M}{\partial x^M} = \frac{\beta_2}{\beta_2 - 1} \frac{U'\left(x^M\right)\left(1 - F\left(x^M\right) + f\left(x^M\right) U\left(x^M\right)\right.}{\left(1 - F\left(x^M\right)\right)^2} \tag{D.3}$$

which is negative if:

$$\begin{aligned} & -\frac{U'\left(x^M\right)}{f\left(x^M\right)} > \frac{U\left(x^M\right)}{\left(1 - F\left(x^M\right)\right)} \\ & -\frac{\sigma'\left(1 - F\left(x^M\right)\right) f(x^M) \left(\left(\bar{x} - x^M\right) - \int_{x^M}^{\bar{x}} F\left(x\right) dx\right) - \left(k - \sigma\left(1 - F\left(x^M\right)\right)\right)\left(1 - F\left(x^M\right)\right)}{f\left(x^M\right)} > \\ & \frac{\left(k - \sigma\left(1 - F\left(x^M\right)\right)\right)\left(\left(\bar{x} - x^M\right) - \int_{x^M}^{\bar{x}} F\left(x\right) dx\right)}{\left(1 - F\left(x^M\right)\right)}. \end{aligned} \tag{D.4}$$

The optimal timing. Let us recall that the growth rate of the investment cost overtime is

$$\frac{dI_t}{I_t} = \mu dt + \eta dB_t \tag{D.5}$$

with expected value and variance respectively equal to

$$\mathbb{E}\left[\frac{dI_t}{I_t}\right] = \mu dt, \qquad \mathbb{V}\left[\frac{dI_t}{I_t}\right] = \eta^2 dt, \tag{D.6}$$

with B_t being a Wiener process characterized by a normal distribution and following features

$$\mathbb{E}\left[B_t\right] = 0, \qquad \mathbb{V}\left[B_t\right] = dt \qquad, B_{t=0} = 0. \tag{D.7}$$

The equation of the investment cost at each time t is then

$$I_t \quad = I_{t_0} e^{\left(\mu - \frac{1}{2}\eta^2\right)(t - t_0) + \eta\left(B_t - B_{t_0}\right)} \tag{D.8}$$

with

$$\mathbb{E}_0\left[I_t\right]=e^{\mu+\frac{1}{2}\eta^2} \tag{D.9}$$

$$\mathbb{V}\left[I_t\right]=e^{2\mu+\eta^2}\left(\eta^2-1\right) \tag{D.10}$$

$$\mathbb{E}_0\left[I_t^2\right]=e^{\left(2\mu+2\eta^2\right)} \tag{D.11}$$

The optimal timing $\mathbb{E}_0\left[\tau\right]$ yields from

$$\int_{t_0}^{T} dI_t=\int_{t_0}^{T}\mu I_t dt+\int_{t_0}^{T}\eta I_t dB_t \tag{D.12}$$

$$I_T-I_{t_0}=\mu\int_{t_0}^{T} I_t dt+\eta\int_{t_0}^{T} I_t dB_t$$

$$I_T=I_{t_0}+\mu\frac{I_t^2}{2}\left(T-t_0\right)+\eta\frac{I_t^2}{2}\left(B_T-B_{t_0}\right)$$

$$I_T=I_{t_0}+\frac{I_t^2}{2}\left[\mu\left(T-t_0\right)+\eta\left(B_T-B_{t_0}\right)\right] \tag{D.13}$$

where if $T=\tau$ we have

$$I_\tau=I_{t_0}+\frac{I_t^2}{2}\left[\mu\left(\tau-t_0\right)+\eta\left(B_\tau-B_{t_0}\right)\right] \tag{D.14}$$

$$\mathbb{E}_{t_0}\left[I_\tau\right]=I_{t_0}+\frac{\mathbb{E}_{t_0}\left[I_t^2\right]}{2}\left[\mu\left(\mathbb{E}_{t_0}\left[\tau\right]-t_0\right)+\eta\left(\mathbb{E}_{t_0}\left[B_\tau\right]-\mathbb{E}_{t_0}\left[B_{t_0}\right]\right)\right]$$

$$\mathbb{E}_{t_0}\left[I_\tau\right]=I_{t_0}+\mathbb{E}_{t_0}\left[I_t^2\right]\frac{\mu}{2}\left(\mathbb{E}_{t_0}\left[\tau\right]-t_0\right) \tag{D.15}$$

and if $t_0=0$

$$\mathbb{E}_0\left[I_\tau\right]=I_0+\frac{\mu}{2}\mathbb{E}_0\left[I_t^2\right]\mathbb{E}_0\left[\tau\right] \tag{D.16}$$

$$\mathbb{E}_0\left[\tau\right]=\mathbb{E}_0\left[I_\tau\right]-I_0-\frac{\mu}{2}\mathbb{E}_0\left[I_t^2\right]$$

$$\mathbb{E}_0\left[\tau\right]=I^M-I_0-\frac{\mu}{2}e^{\left(2\mu+2\eta^2\right)} \tag{D.17}$$

with I^M obtained from Eq. (24).

Appendix E - The social optimum

Let us recall that

$$V(x^W) = \int_{x^W}^{\bar{x}} x(k-\sigma(1-F(x)))dF(x) + R(h(\hat{\theta}), 1-F(x^W)) - [1-F(x^W)]\Psi(\hat{\theta}). \tag{E.1}$$

By using the FOC described by Eq. (28) and with some algebra we obtain:

$$\int_{x^W}^{\bar{x}} x(k-\sigma(1-F(x)))dF(x) + R(h(\hat{\theta}), 1-F(x^W)) - [1-F(x^W)]\Psi(\hat{\theta}). \tag{E.2}$$

$$\int_{x^W}^{\bar{x}} x(k-\sigma(1-F(x)))dF(x) + R(h(\hat{\theta}), 1-F(x^W)) - [1-F(x^W)]\left[x^W(k-\sigma(1-F(x^W))) + \frac{\partial R}{\partial m}\right]$$

$$\int_{x^W}^{\bar{x}} x(k-\sigma(1-F(x)))dF(x) - [1-F(x^W)][x^W(k-\sigma(1-F(x^W)))]$$

$$\begin{aligned}&\int_{x^W}^{\bar{x}} x(k-\sigma(1-F(x)))dF(x) - \int_{x^W}^{\bar{x}} x(k-\sigma(1-F(x^W)))dF(x) + \\ &\int_{x^W}^{\bar{x}} x(k-\sigma(1-F(x^W)))dF(x) - \int_{x^W}^{\bar{x}} x^W(k-\sigma(1-F(x^W)))]dF(x)\end{aligned}$$

$$\int_{x^W}^{\bar{x}} x[(k-\sigma(1-F(x))) - (k-\sigma(1-F(x^W)))]dF(x) + \int_{x^W}^{\bar{x}} (x-x^W)(k-\sigma\left(1-F\left(x^W\right)\right))dF(x)$$

$$\int_{x^W}^{\bar{x}} x[\sigma(1-F(x^W)) - \sigma(1-F(x)))]dF(x) + \int_{x^W}^{\bar{x}} (x-x^W)(k-\sigma\left(1-F\left(x^W\right)\right))dF(x).$$

Appendix F - Comparison of the two scenarios

Proof of proposition 4. By taking the derivative, we obtain:

$$\begin{aligned}\frac{\partial\hat{\theta}}{\partial x} &= -\frac{\frac{\partial^2 R}{\partial h \partial m}\frac{\partial m}{\partial x} + f(x)\psi(\hat{\theta})}{SOC} \\ &= -\frac{f(x)[-\frac{\partial R}{\partial h} + \psi(\hat{\theta})]}{SOC} \\ &= -\frac{f(x)[-[1-F(x)]\psi(\hat{\theta}) + \psi(\hat{\theta})]}{SOC} \\ &= -\frac{f(x)[F(x)\psi(\hat{\theta})]}{SOC} > 0\end{aligned} \tag{F.1}$$

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