Renewable energy communities, digitalization and information.

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Motivation and background

Renewable Energy Communities (REC)

The **evolution of energy markets** towards a more **decentralized and decarbonized** dimension is connected to **Renewable Energy Communities**.

ICT is needed to collect information within the REC to coordinate phases of production and consumption, so that the **exchange of energy** occurs, self-consumption is maximize.

Such **data have a social and economical dimension** as well as privacy implications

Renewable energy communities general framework (European Commission)

Citizen-driven (municipalities as well) energy actions	Agents (local institutions)
Contributing to the clean energy transition	Decarbonisation Targets
Means to re-structure and harness whole energy system	Digitalization + ICT
Advancing energy efficiency and independency at local level	Decentralization

Our modelling focus is on the **optimal sizing and set up drivers** of the RECs, in an analytical framework with **information collection and agents' privacy externality.**

The model

Assumption - The municipality and the investment

A **municipality** (benevolent planner), is willing to **pay the cost** mI (RE plants, storage facilities and connections to the local grid) **for the REC establishment**, where:

- m is the number of the **members of the REC** (its dimension as well).
- I the **unitary overall cost of the investment** per member.

The sunk investment I per member, is **stochastic** and evolving overtime according a Geometric Brownian Motion (GBM):

$$dI_t = \eta I_t dt + \sigma_t dB_t \quad \text{with} \quad I_{t=0} = I_0, \tag{1}$$

with drift rate $\eta < 0$, volatility rate σ and dB_t the increment of the standard Wiener's process, satisfying $\mathbb{E}\left[dB_t\right] = 0$ and $\mathbb{E}\left[dB_t^2\right] = dt$.

Assumption - The aggregator

The management of the REC is granted to a **profit maximizer aggregator A** after the payment of a concession fee w to the municipality.

The aggregator:

- **provides all the ICT** needed from the REC members to optimize their energy consumption (**SG, smart grid**) and overall REC operation;
- **collects information** $h(\theta)$ concerning the REC members' behavior, through the SG service, with a certain **level of detail** $\theta \in [0, 1]$:

  for $\theta \to 0$: collection of **basic information**, such as size of the PV plant,

  for $\theta \to 1$: collection of **detailed information**, such as instantaneous energy consumption per device type.

The aggregator decides to collect all types of information in the interval $[0, \hat{\theta}]$, thus the overall measure of the information collected is:

$$h(\theta) = \int_0^{\hat{\theta}} dG(\theta). \tag{2}$$

Assumption - The aggregator

In addition to that, the aggregator

- **sells additional energy needed by the REC members at price** p.
  By assumption REC energy demand exceed its inner energy production and the aggregator **is the sole supplier of energy for the REC members**.
- **sells collected information** $h(\theta)$ to **third parties** gaining revenues:

$$R(h(\theta), m) = mbh(\theta). \tag{3}$$

  that are increasing in both h and m and concave in h, while $b > 0$ represents the unit price of data.

Assumptions - The agents

In our framework, there is a **mass equal to 1 of energy users**, characterized by **same level of energy demand** ($k = 1$), with symmetric patterns, which is satisfied as follows:

$$1 = \text{energy purchased} + r\left(m\right), \tag{4}$$

where $r\left(m\right)$ is the **energy overall self-consumed within the REC**.

The agents are heterogeneous in valuating the services provided by the REC:

- $x \in [\underline{x}, \overline{x}]$: the **willingness to pay for one unit of energy provided by the aggregator**
- $x\left(1-\gamma\right)$, $\gamma > 0$: **willingness to pay for one unit of energy produced within the REC**, thus $r\left(m\right)$, with $\gamma \in [0; \bar{\gamma} \ll 1]$ capturing the **potential decrease in value that the REC members** attribute to the public good characteristic of self-produced energy as its cost is null

Assumptions - The agents

Each member of the REC is subject to a **dis-utility due to the information collection**, which we define as **privacy cost** $\psi(\theta)$

$$\Psi\left(\theta\right) = \int_0^\theta \psi\left(\theta\right) dG\left(\theta\right), \tag{5}$$

and increasing in θ, the level of detail, identified by the aggregator.

The agents' **utility function** is then:

$$u\left(m, p, \hat{\theta}\right) = (x - p)(1 - rm) + x\left(1 - \gamma\right) rm - \Psi\left(\theta\right) \tag{6}$$

- the agents' valuation of the energy purchased net of the price,
- the energy residual demand of the REC's members,
- the utility associated to the renewable energy produced within the REC
- the privacy loss

Assumption - The Renewable Energy Community (REC)

The **REC dimension** m **is determined on the basis of the agent's valuation** x, namely:

$$m = 1 - F(x) \qquad x \in [\underline{x}, \overline{x}] \tag{7}$$

where $F(x)$ is the distribution function of x.
The latter represents the cutoff type such that all the consumers whose valuation exceeds or equals x, **will join the REC.**

- $\rightarrow$ If $x = \underline{x}$ then $m = 1$, the REC reaches the maximum dimension.
- $\rightarrow$ If x is sufficiently high, respect to the lower bound $\underline{x}$, all agents becomes REC members.

The private equilibrium

The aggragator solves the following **optimization problem**:

$$\max_{p} \int_0^{\infty} \pi(m) e^{-rt} dt, \tag{8}$$

$$\text{s.t.} \quad u(m) \geq \overline{u} \quad \text{for all} \quad t \geq 0, \tag{9}$$

$$\pi\left(m, p, \hat{\theta}\right) = mp(1 - rm) - mw + mbh(\theta), \tag{10}$$

with $\overline{u} = 0$ and $\pi(m)$, the per-period profit function, as the sum of:

- the revenues from the sale of energy to the members of the REC,
- the fee paid for the REC operation,
- the revenues gained from the sell of collected information.

$\rightarrow u(m) \geq \overline{u}$: Individual Rationality (IR) constraint, with $\overline{u}$ the reservation utility, minimum level that must be guaranteed by a contract to make it acceptable.

The aggregator will identify x^M, as **the profit-maximizing optimal cutoff type of agents' valuation**, determining then **the optimal REC size** $m^M = 1 - F\left(x^M\right)$, as a result of the FOC:

$$\underbrace{\left[x^M - \frac{1 - F\left(x^M\right)}{f\left(x^M\right)}\right]\left[1 - \gamma r\left(1 - F\left(x^M\right)\right)\right]}_{\text{Virtual valuation of the energy provided to each consumer}} - \underbrace{\gamma r\left(1 - F\left(x^M\right)\right)x^M}_{\text{Loss for A due to consumers' energy devaluation}}$$

$$\underbrace{+bh(\theta)}_{\text{Marginal revenue from data sales}} = \underbrace{w + \Psi\left(\theta\right)}_{\text{Marginal cost}}, \tag{11}$$

which in turn will define the price of energy p^M and the REC utility U^M:

$$p\left(X^M\right) = \frac{x^M\left(1 - \gamma r m^M\right) - \Psi\left(\theta\right)}{1 - r m^M}, \tag{12}$$

$$U\left(x^M\right) = \int_{x^M}^{\bar{x}} u\left(x, x^M\right) dF\left(x\right) = \left[1 - \gamma r\left(1 - F\left(x^M\right)\right)\right]\int_{x^M}^{\bar{x}}\left(x - x^M\right) dF\left(x\right) \tag{13}$$

The private equilibrium

Outcomes

Table 1: Changes in agents' valuation $\left(\frac{\partial x^M}{\partial \ldots}\right)$ and REC size $\left(\frac{\partial m^M}{\partial \ldots}\right)$

Parameters	∂	*Valuation* x^M	*REC size* m^M
Information detail	θ	+	-
Cost paid by A	w	+	-
Price of data	b	-	+
Energy devaluation	γ	-	+
Self-consumption efficiency	r	-	+

Remarks: although the latter result seems contradictory, it is not. In both cases the effect is a reduction (albeit by different routes) in the utility of the REC members, which in turn has a spillover effect on the aggregator's profits through a reduction in the price of energy that prompts the aggregator to increase m^M

The public equilibrium

- The municipality retains control and rights during the project life.
- **The REC is managed by a public owned firm**, still collecting information.
- This set up leads to a larger participation in the REC and more self-consumption.

The optimization problem the municipality, determining the social cutoff x^W, is then:

$$\max_{x} \quad V(x,\hat{\theta}) \quad \text{with:} \tag{14}$$

$$V\left(x,\hat{\theta}\right) = \int_{x}^{\bar{x}} \left[y\left(1-r\right) + y\left(1+\gamma\right)rm\right] dF\left(y\right) \tag{15}$$

$$+\left[1-F\left(x\right)\right]\left[bh\left(\theta\right) - w - \Psi\left(\theta\right)\right]$$

- aggregate total utility of the REC members,
- revenue from the sale of data net of the cost of managing the REC and the privacy cost.

Optimality conditions across cases

Public equilibrium

$$\underbrace{x^W\left[1-\gamma r\left(1-F\left(x^W\right)\right)\right]}_{\text{Valuation}}+\underbrace{bh\left(\theta\right)}_{\text{Marginal revenue}}=\underbrace{w+\Psi\left(\hat{\theta}\right)}_{\text{Marginal Cost}}$$

Private equilibrium

$$\underbrace{\left[x^M-\frac{1-F\left(x^M\right)}{f\left(x^M\right)}\right]\left[1-\gamma r\left(1-F\left(x^M\right)\right)\right]}_{\text{Virtual valuation of the energy provided to each consumer}}-\underbrace{\gamma r\left(1-F\left(x^M\right)\right)x^M}_{\text{Loss for A due to energy devaluation}}$$

$$\underbrace{bh(\theta)}_{\text{Marginal revenue from data sales}}=\underbrace{w+\Psi\left(\theta\right)}_{\text{Marginal cost}},\tag{16}$$

The investment problem for the municipality

- The municipality must solve, at time $t = 0$, an optimization problem in each of the two scenarios s (17),
- to *identify the best investment decision*, thus **investment cost threshold** (18), and **structure for the best REC set up according to her objectives**.

$$O^s\left(I_0, m^s\right) = \max_{I^s} \left(\frac{I_0}{I^s}\right)^{\beta} \left[\Omega\left(s\right) + m^s\left(w - \rho I^s\right)\right] \quad s = \{M, W\} \tag{17}$$

$$\rho I^s = \frac{\beta}{\beta - 1}\left[\frac{\Omega\left(s\right)}{m^s} + w\right] \tag{18}$$

$$\text{with} \quad \Omega\left(s\right) = \begin{cases} U\left(m^M\right) & \text{if} \quad s = M \\ V\left(m^W\right) & \text{if} \quad s = W \end{cases} \tag{19}$$

where $\left(\frac{I_0}{I_\tau}\right)^{\beta}$ as the expected discount factor, with $\beta < 0$ (**?**).

Discussion

Main outcomes

- **The size of the REC set by the aggregator is smaller** than that determined under the management of the municipality, $m^M < m^W$.
- The **utility of the REC under the management of the aggregator is lower**, $U\left(m^M\right) < V\left(m^W\right)$.
- **The aggregator invests later**, $I^M < I^W$ (recall that by assumption $\eta < 0$, the investment cost decreases overtime).
- The **widening of the depreciation parameter** γ, associated with the valuation of the energy provided by the REC, and the **efficiency parameter** r, the **bigger is the REC size in both scenarios**.

Discussion

If we consider the public regime as a benchmark, we can ask **what interventions can align private management with public management, i.e.** $\Delta m = m^W - m^M = 0$ **and** $\Delta I = I^W - I^M = 0$?

- **The municipality can incentivize the aggregator by setting** $w' < w$, assuring a reduction in Δm as $m^M(w') > m^M$.
- However, this results in a **reduction in the revenue that the municipality** receives from the aggregator, making the effect on ΔI uncertain.
- That is, for an increase in $\frac{U\left(m'^M\right)}{m'^M}$ there is a decrease in w'.
  A condition for this intervention to reduce ΔI is that:

$$\frac{\partial\left(m^M w\right)}{\partial w} = \frac{f\left(x^M\right)w}{SOC} + \left(1 - F\left(x^M\right)\right) < 0 \qquad (20)$$

Discussion

- **The municipality may ask the aggregator to burden also a share of the overall investment cost** for the REC set up, i.e. αI, reducing the public financial effort to $(1-\alpha)I$.
- However, this implies **a decrease in the REC size**, i.e. $(m')^M < m^M$, **without assuring any positive effect on the side of the investment timing**, that is defined by:

$$\rho I'^M = \frac{\beta}{\beta - 1}\left[\frac{\frac{U\left(m'^M\right)}{m'^M} + w}{1-\alpha}\right], \tag{21}$$

where $I'^M > I^M$ only if the decrease in $\frac{U\left(m'^M\right)}{m'^M}$ is counterbalanced by the reduction in cost.

Discussion

We can then consider the case where the central government decides to **tax the revenues from the sale of information** and **transfers the collected funds directly to the municipality**, i.e. $b' = b + \omega$.

- **The decrease in** θ that is generated results in a **reduction in both the privacy cost and revenues.**
- Although the two effects neutralize leaving the size of the REC unchanged, **the investment is anticipated** i.e.:

$$\rho I'^{M} = \frac{\beta}{\beta - 1}\left[\frac{U\left(m^{M}\right)}{m^{M}} + w + \omega h\left(\hat{\theta}\right)\right] > \rho I^{M} \tag{22}$$

Numerical exercise

To illustrate the results, we consider a simple parametric example assuming that:

- in the case where the REC is operated by the **municipality**, for ethical reasons, she **cannot collect and sell consumers' information**.
  This set up is introduced assuming that the price of data $b = 0$ for the municipality so that $\theta^W = 0$, while
- **for the aggregator**, the price of data is $b = 1$ which, in turn, means that the **types of information collected is the maximium**, $\theta^M = 1$.
- **An higher cost is paid in the case of private management of the REC**, thus $w^W \leq w^M$, with $w^W = \frac{1}{2}$, $w^M \in \left(\frac{1}{2}, \frac{8}{3}\right]$.
- $F(x) = x$, $G(\theta) = \theta$ and $h(\theta) = \theta$;
- $\Psi(\theta) = \int_0^\theta \psi(s)\, dG(s) = \frac{2}{3}\theta^{3/2}$.

What we want to find now is the level of w^M that the municipality should accept from the aggregator, such that $m^M = m^W$, thus the REC size under the private management equals the social optimal one.
This is achieved under the following constraints:

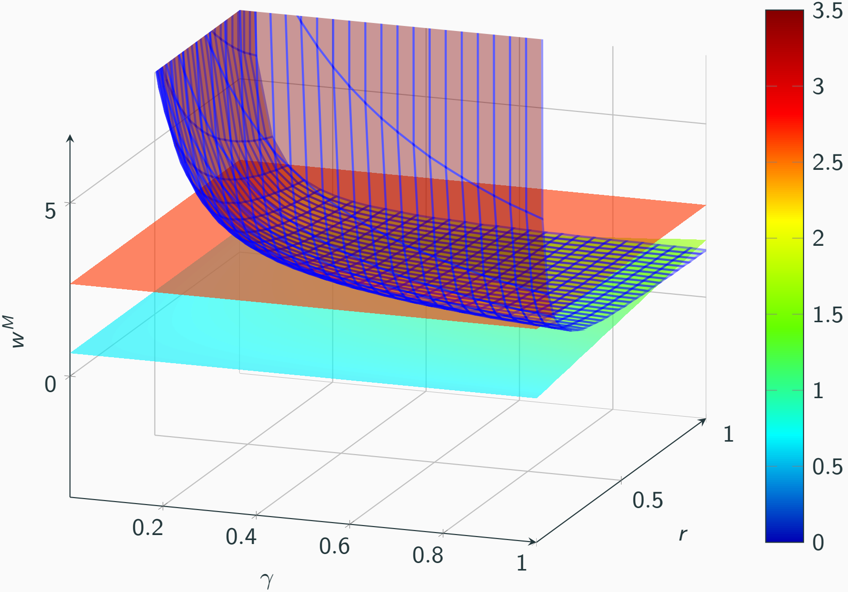
$$x^M < 1 \qquad \text{if} \qquad w^M < \frac{8}{3}; \tag{23}$$

$$x^M > 0 \qquad \text{if} \qquad w^M > \left(\gamma r + \frac{2}{3}\right); \tag{24}$$

$$x^M \leq x^W \qquad \text{if} \qquad w^M \leq \frac{\gamma r}{2} + \frac{3}{2} + \frac{(1 - 3\gamma r)\sqrt{1 + (\gamma r)^2}}{6\gamma r} - \frac{1}{6\gamma r}. \tag{25}$$

all expressed as a function of γ, the energy devaluation parameter and r, the efficiency parameter associated to the self-consumption of the energy produced by the REC.

Numerical exercise



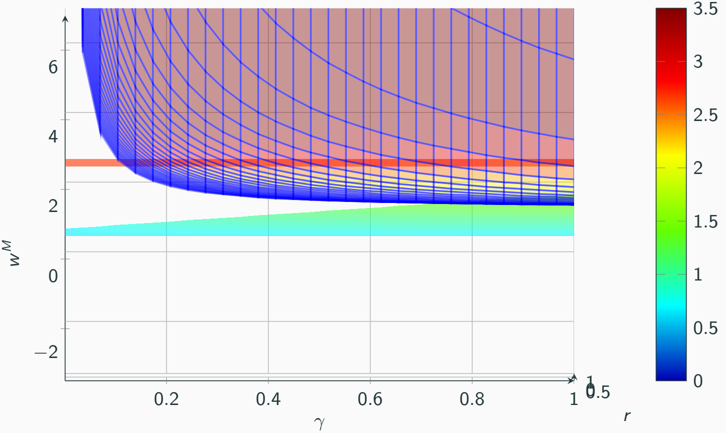


Figure 2: γ limit

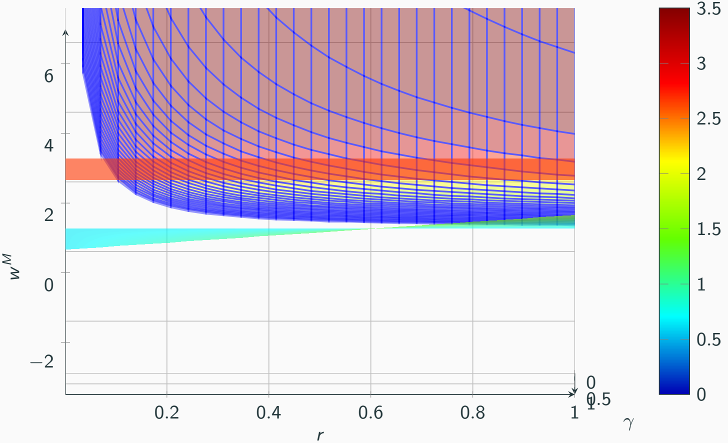
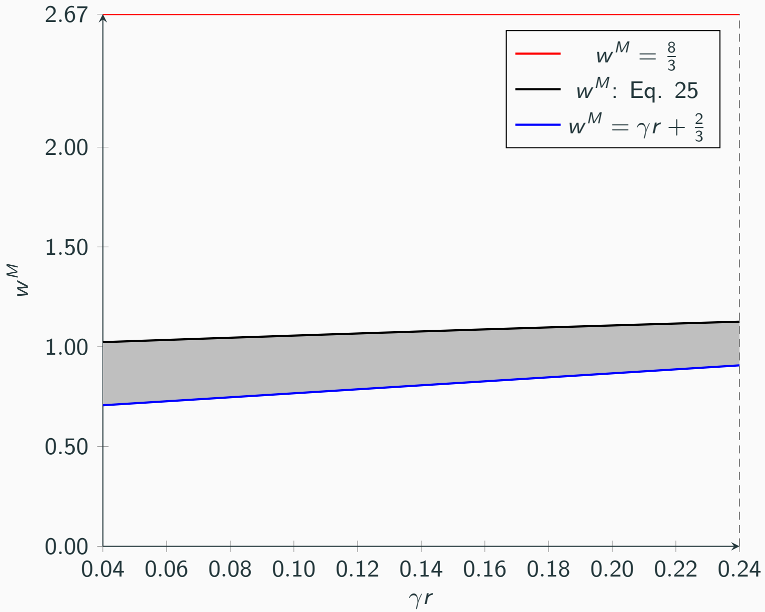
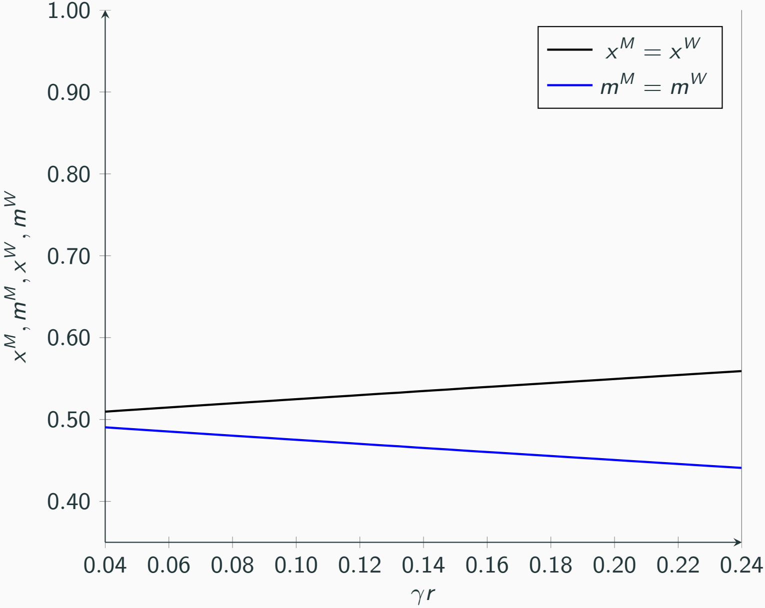


Figure 3: r limit

Numerical exercise





1.00
0.90
0.80
0.70
0.60
0.50
0.40
x^M, m^M, x^W, m^W
$x^M = x^W$
$m^M = m^W$
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
γr

Numerical exercise

From the last two figures we can obtain some numbers:

- $\forall \gamma r \in [0.04; 0.24]$, which means:
- $\gamma \in [0.20, 0.40]$ and $r \in [0.20, 0.60]$,

when the aggregator pays $w^M \in [1.022932; 1.125522] > w^W$:

- $x^M = x^W \in [0.509996; 0.55916]$
- $m^M = m^W \in [0.44084; 0.490004]$: social optimum, but half of the max size.

If $\gamma = 0$, i.e. no devaluation is associated to the energy produced by the REC:

- $x^M = \frac{w^M}{2} - \frac{1}{3}$ and $x^W = w^W = \frac{1}{2}$
- $x^M \leq x^W$ if $w^M \left(\frac{1}{2}, \frac{5}{3}\right]$: change in the constraint
- when $w^M = \frac{5}{3}$, the valuations equals, thus $x^M = x^W = w^W = \frac{1}{2}$, and the REC sizes become $m^M = m^W = \frac{1}{2}$

$\rightarrow$ if the devaluation γ is positive, the cost w^M basically doubles, the valuations decreases and the size increases

Conclusions

Conclusions

At this stage, we are able to:

- discuss the role of **private information collection costs** on determining the willingness of **agents to participate in a REC**, studying the **REC sizing problem**,
- accounting for the **privacy cost each agent** has to incur in, after entering in the REC, and **uncertainty** of the side of the **investment cost**.
- under to different scenarios, **monopolistic / profit-miximizing** one and **utilitarian one**,
- deepening in particular the **role of the aggregator**

in a framework where:

- the **capacity** of the renewable energy infrastructure is **exogenous**.
- REC's **members** are **not allowed to sell or buy energy** outside of it.

Conclusions

Summary of the outcomes

- Although financed by the municipality, **the REC has a lower optimal size when managed by an aggregator**.
- consequently, **the investment is also delayed** compared to the case where it is managed directly by the municipality.
- Such effect can be mitigated if a **proper fee** w^M **for the REC management** is set by the municipality.
- Even though the issue of **agents' privacy loss** is yet to be perceived in reality, our aim is to draw the attention of policy makers on this side for a **proper regulation design**.

Work to be done

- Numerical exercise focusing on investment decision
- Policy recommendations

Thank you for your time.

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