DIRK BERGEMANN
Yale University
MARINA BERTOLINI
University of Padova, Levi Cases Centre and CRIEP
Marta Castellini
University of Padova and FEEM
MICHELE MORETTO
University of Padova
SERGIO VERGALLI
University of Brescia and FEEM

OPTIMAL MANAGEMENT OF PUBLIC ENERGY COMMUNITIES: INVESTMENT STRATEGIES AND WELFARE MAXIMIZATION

September 2025
Marco Fanno Working Papers – 325

dSEA Dipartimento di Scienze Economiche e Aziendali 'Marco Fanno'
Università degli Studi di Padova

Optimal management of public energy communities: investment strategies and welfare maximization

Dirk Bergemann*, Marina Bertolini§,¶, Marta Castellini†,‡, Michele Moretto‡, Sergio Vergalli†,**

Abstract

A municipality (social planner) is seeking to establish a renewable energy community paying the initial investment costs, while also identifying the optimal management framework. In this context, two distinct modes of governance are analyzed: the private and the public one. In the first case, a private (or profit) aggregator oversees the energy community with a monopolistic behavior, while in the other the aggregator is a public owned, or controlled, company following the social approach advocated by the promoter, i.e the municipality. In both scenarios, the effective functioning of the community requires the collection of private data on members' energy consumption. This process allows for optimal management of the community, but also results in a loss of privacy for members. The model incorporates this as a dis-utility, assuming that the members address the portion of their energy needs not covered by the community's production by purchasing energy from the manager at a price determined on the basis of the information collected. In addition, the aggregator is allowed to sell the collected data to third parties for financial gain. By integrating the members' energy valuation and incorporating uncertainty regarding the investment cost, we examine policy recommendations aimed at establishing a community size closer to the social optimum.

Keywords: Renewable Energy, Renewable Energy Communities, Digitalization, Information, Privacy.

JEL Classification: Q42, C61, D81

*Department of Economics, Yale University, USA; † Fondazione Eni Enrico Mattei - FEEM, Italy; ‡Department of Economics and Management, University of Padova, Italy; §Department of Statistical Science, University of Padova, Italy; ¶Levi Cases Centre and CRIEP, University of Padova, Italy; **Department of Economics and Management, University of Brescia, Italy.

1 Introduction

The twin challenges of decarbonization and digitalization are reshaping energy systems. This process involves both infrastructure and markets, with the entry of new operators and a change in the traditional roles of agents. These changes also require significant investment and organisational effort, including from a policy perspective.

With the transition from fossil fuels to a greater use of renewable and clean sources, energy production and management must move to a more decentralized model. With the installation of renewable energy systems of modest size, or even tailored to domestic loads, energy consumption is now close to local production.

In this vein, Renewable Energy Communities (RECs) enable energy consumers and small-scale producers to collectively generate and share clean energy within their network. In their original and theoretical intent, these organizational frameworks were expected to democratize energy production while also advancing sustainability goals and affordability. However, their successful implementation requires careful consideration, from governance structures to the growing role of data in energy management.

Our work explores a critical and, in our view, under-researched area in relation to this type of community when the decision to create it is taken by a social planner (her). Specifically, our model takes into account: i) the dynamics of the investment costs that she has to bear for the creation of the community, ii) her decision on the type of its governance (private/public management), while also considering iii) the willingness to pay for green energy of the private agents, who are also potential members of the community, and accounting for iv) the role of digitization, meaning that the collection of private information from agents is on the one hand necessary to ensure both economic and technical optimality of such a system, but on the other hand generates dis-utility for the members of the community in the form of loss of privacy.

Therefore, we have decided to analyse this domain by associating the social planner with an ideal local municipality that is willing to carry out such an initiative, while also considering the new digital facet surrounding the initiative, not only on the side of the agents, but also focusing on the company managing the community, that we define "aggregator", who in our framework is allowed to sell the data collected to third parties.

1.1 The challenge

Assuming that the initiative to set up the REC is taken by a public body - in our case, a municipality - a fundamental decision at the time of establishment is whether to retain public control or to delegate management to private operators. This is a classic issue in public finance and falls within the wider field of public-private sector relations: often public authorities do not have the technical expertise to keep up with the most advanced technologies and complexity of organization framework, and finding a qualified private partner can make the difference in terms of performance.

In the case of RECs, efficient execution of tasks for their functioning requires also expertise in data management (López et al., 2024; Schaefer et al., 2023). The decision to maintain (or not) public control over the initiative has significant implications for community participation in the project, operational efficiency in terms of energy management as well as privacy implications. In the private market, operators (aggregators, Petrucci et al. (2023))

often have technical expertise in energy optimization, but may prioritize profit over community welfare, including privacy, or overall environmental performance.

Meanwhile, the digital infrastructure that is essential for communities to operate efficiently generates valuable data about members' energy consumption patterns, data that has both operational utility and commercial value. This creates a trade-off, as the information that enables optimal energy management can also be used to generate revenue in ways that may compromise member privacy or lead to discriminatory pricing.(Zhang et al., 2023; Rhodes and Zhou, 2024). Community members thus face a "privacy cost" alongside the benefits for their "prosumerism", thus their choice of taking part to the project producing and consuming renewable energy, while also modulating their energy demand (Brown et al., 2020)

1.2 Our contribution

Our theoretical framework analyses all these features through a model that can derive several findings relevant to the literature on the decentralization and digitalization of energy markets and public choices. This is achieved by studying the establishment of energy communities.

This study examines the decision-making process of a public entity that has committed to investing in an energy community. The entity must then decide whether to retain direct management of the community or delegate it to a private actor, such as an aggregator. For the purposes of our evaluation, we consider not only the overall utility generated by the community but also two additional factors: the time required to implement the investment (time to investment) and the size of the community in terms of number of participating members.

A distinctive feature of our analysis lies in the inclusion of a "privacy cost" within the cost function of potential participants. Compared to previous evaluations on the subject, this element represents a novel contribution, as it takes into account individual concerns relating to data privacy when deciding whether to join the energy community. The cost of privacy is interpreted as the risk that citizens incur when entrusting their personal information to the telecommunications network that supports the management of the community. This exposure may lead to potential hacking incidents and the theft of personal data.

As a first step, we focus on the private governance case to study the equilibrium of the profit maximizing aggregator and how key features of the model affect the sizing of the community (Proposition 3). The number of members increases if the aggregator receives a higher price for information, while it decreases when the cost paid to the municipality for operating the community rises, as well as when the agents value more the energy produced by the community or technological improvements allow for higher green energy consumption. The public governance case is then created assuming that the municipality retains control over the community entrusting a public owned company and thus the optimal size yields from the maximization of the social welfare function. The comparison of these two cases (Proposition 5) shows that: i) the size of the community is smaller when it is run by the aggregator; ii) the community utility is higher when it is managed by the aggregator; iii) the municipality invests sooner in the private governance case.

A numerical example is used to determine the conditions under which the private governance framework could be aligned with the public one. Specifically, the focus is on ensuring the size of the community is socially desirable. In addition, we also consider the case in which the municipality manages the community and no information is collected. Thanks to this example it is also possible to assess the role played by the level of environmental awareness (i.e. the value members assign to the green energy produced by the community) on the strategy of the public authority, as for small, highly motivated communities, the public governance must be preferred; vice versa, if citizens are not too "environmentally involved", private governance would be preferred, also allowing for larger communities.

1.3 Policy relevance

With initiatives like the European Union's Clean Energy Package (EU, 2019) and similar frameworks emerging globally, RECs are starting to be recognized as powerful instruments to foster citizen participation in the energy transition. These communities represent a unique opportunity to democratize energy generation and consumption, aligning local action with global sustainability objectives. However, the regulatory environments governing data rights, privacy, and community management are still evolving, posing challenges and opportunities for policymakers and practitioners alike.

Our work sheds light on the relationships between governance structures, privacy considerations and community outcomes, providing insights for RECs' stakeholders. In particular, we provide practical guidance for policymakers seeking to structure effective public-private partnerships that take advantage of the strengths of both sectors to maximize the impact of community energy projects. In addition, we highlight that the design of robust privacy frameworks can protect individual privacy without compromising the operational needs of REC management.

Regulation should develop targeted incentive mechanisms that align private management strategies with broader public interests, ensuring accountability and shared benefits.

Beyond these specific recommendations, our research introduces a theoretical framework that extends beyond the energy sector. By examining RECs as a case study, we offer insights of wider relevance to other areas where public services are increasingly reliant on private management and data-driven optimization.

Similarly, we notice a relevant impact of consumers' sensitiveness towards environment on investment valuation results. This framework underscores the importance of balancing efficiency with equity and technological advancement with ethical management.

Our findings emphasise that the implementation of successful RECs requires a nuanced approach to governance and privacy. While the expertise and resources of the private sector can significantly improve operational efficiency, robust public oversight is essential. This could safeguard community interests and ensures that the RECs realise their full potential as catalysts for environmental progress and social cohesion.

1.4 Related literature

Over the past decade, various countries worldwide have begun to consider how to directly involve citizens in decarbonizing their economies and managing energy systems. To make this decentralized model effective, infrastructures and markets need reorganization to increase the inclusion of these new. actors (Agostini et al., 2021). Compared to other investments in the energy sector, the main novelty in this local markets is the need of large and finer data exchange that allows for an effective integration of renewable sources (Zheng and Wang, 2021) in the system and for a greater participation of citizens in the market (Mansoor and Paul, 2022). This data exchange is necessary for community functioning and energy management optimization (Hao et al., 2025; Xu et al., 2022), but it also represents a "new" investment cost: the cost of privacy.

We consider a digital context, taking into account the value of the information that must be collected for the optimal operation of the community and the associated loss of privacy for community members, thus contributing to another relevant issue that arises with the digital transition, as already discussed in Choi et al. (2019); Bergemann et al. (2022) and Galperti et al. (2023), among others. Acquisti et al. (2016) detailed as well how privacy has economic implications in the choices of agents.

It is worth reporting that there are other aspects that can slow down or prevent the implementation of what are defined as "smart networks"(De Wildt et al., 2019), but in this work we have chosen to develop a theoretical framework about energy community governance that is able to take into account also the digital domain and thus the role of data exchange.

By examining the process a municipality undergoes to establish the community, with a focus on identifying the most effective governance structure for its management, our aim is to determine whether private or public governance is more appropriate according to different objectives, i.e welfare improvements, community size, members' participation, renewable energy consumption and/or investment timing. The subject of the work is a well-established topic in the public finance sector (Bennett and Iossa, 2006). As already happens in other cases of highly specialized investments (Carbonara and Pellegrino, 2020), collaboration between public and private is widely used, but moving management from public to private can lead to a reduction in welfare. Moore et al. (2017) explicitly took the social welfare perspective in analyzing the utility service sector, and we can consider this sector to be fairly close to our target. The typical theme of risk sharing between public and private agents (Carbonara et al., 2014; Takashima et al., 2010) is relevant for us considering both the participation rate and the consumption behavior of citizens.

As highlighted by Moore et al. (2017), also in our model the typical problems of the principal-agent relationship are recognizable, since the private aggregator's ability to manage the community has an impact on its performance, so the choice of private aggregator is important. This aspect is not analyzed in our model, but it is reasonable to assume that it would have an impact in the initial bargaining phase (Bottom et al., 2006) where frictions emerge with different intensity depending on technology involved in the project (Schmitz, 2015).

With this domain in mind, we contribute to the literature on public-private cooperation by presenting the comparison between the scenario in which the entity setting up and managing the energy community is public and, instead, the scenario in which the public entity builds the community and then entrusts a private entity with the task of managing it, in exchange for a pre-established fee.

Overall, the work fits into the literature related to solutions for the energy transition. The reference stream is that of renewable energy and energy communities, recently discussed - among others - by Srithapon and Månsson (2023) and Luzzati et al. (2024) on the theme of flexibility, provided that citizens are sensitive to energy prices in their everyday choices (Houde and Myers, 2021). Schrammel et al. (2023) worked on the sensitivity of households to prices, detecting a general interest, the main barriers being limitations in the flexibility potential of households and limited perceived benefits. Automated demand-side management seemed to be well accepted. However, in an applied study, Wörner et al. (2022) found that the stated pro-environmental behavior is weakened in the bid phase while analyzing the Prosumer to Prosumer (P2P) energy market with renewables. The attitude towards the environment is relevant in our work, as consumers give extra value to the energy they *prosume*. In the literature, we can find several studies that take this aspect into account while considering the aggregate demand of environmental-conscious consumers (Conrad, 2005; Han et al., 2023).

From a methodological perspective, the reference works are that of Choi et al. (2019) and Bergemann et al. (2022) while concerning modelling investment in renewable energy we refer to research carried out using the real option theory (Yang et al., 2024; Andreolli et al., 2022; Castellini et al., 2021a,b; Bertolini et al., 2018). Models on neighboring topics were also developed in Li et al. (2021) for optimal pricing in the smart grid and Schrammel et al. (2023) to test the interest of consumers in price signals. The approaches that are closer to ours are those of Clò et al. (2025) and Loisel and Lemiale (2023), both of which take a welfare perspective. The former mostly focuses on comparing bottom-up and top-down energy community frameworks, while the latter deals with surplus energy and the rules for sharing it.

2 The model

Consider a local public authority (henceforth "a municipality", she) that is willing to pay the cost of setting up a renewable energy community (henceforth "community") for the local energy consumers. The investment cost includes the installation of renewable energy plants, storage facilities as well as connections to the local grid.

Once the community is established, the municipality decides on the type of governance between entrusting the management to a publicly owned company or outsourcing the management to a private operator (henceforth "aggregator", he).[1]

In both scenarios, community management allows some private information to be collected about how each community member uses energy, which can lead to a loss of privacy if used for purposes other than optimal community management.[2] In addition, both the private operator and the public utility have an obligation to cover the additional energy that the community is unable to self-produce to meet the entire demand. This task is fulfilled selling additional

[1] In line with Laffont et al. (1993), the public regime is the one in which the municipality makes the investment and retains control throughout the life of the project.

[2] Note that optimal community management requires information gathering. For example, to better coordinate energy sharing between members through the use of energy optimization software and/or smart home solutions. Loss of privacy refers to the distorted and improper use of this information by management.

energy to the members of the community in exchange of a certain price [3].

Before discussing the equilibrium analysis, let us present the characteristics of the agents involved in the private governance.

The consumers There is a number of consumers of mass 1 who may consider joining the community. Each of them obtain utility from the consumption of the energy, both from that produced by the community, which we define also as "self-consumption", and from that purchased from the aggregator. Each consumer has the same energy need, normalized to 1. Defining $m \leq 1$ as the number of community members, the energy requirement is then covered as follows:

$$1 = q + r(m) \tag{1}$$

where q denotes the energy obtained by the aggregator and $r(m)$ the share of self-consumed energy available to each member. Thanks to the community setting, $r(m)$ is an increasing function of the number of the members m, with $r(0) = 0$ and $r(1) < 1$.[4] Without loss of generality, we use a linear function to describe self-consumption:

$$r(m) = rm, \tag{2}$$

where $r < 1$ indicates the efficiency level that the community management is able to achieve in terms of self-consumed energy.[5]

Consumers are heterogeneous in their willingness to pay for energy $x \in \mathbb{R}_+$, which is distributed on $[\underline{x}, \overline{x}]$ according to the cumulative distribution function $F(x)$, with density $f(x)$ and mean $\mathbb{E}[x] = \lambda$. The distribution $F(x)$ is such that $\frac{1-F(x)}{f(x)x}$ is monotone and decreasing, with $f(\overline{x}) > 0$ and $1 < f(\underline{x})\underline{x} \leq \frac{3}{2}$. According to the distribution function $F(x)$, the mass of consumers m that join the community will be:

$$m = 1 - F(x), \tag{3}$$

where x indicates also the cutoff type such that all the consumers whose willingness to pay exceeds or equals x will join the community.[6] In addition we distinguish between the willingness to pay for the energy purchased and that produced by the community. Namely, the willingness to pay for the latter is $(1+\gamma)x$, where the parameter $\gamma > 0$ captures the potential increase in value that members of the community attribute to the low environmental impact of self-produced energy. While x refers to that sourced from the aggregator. As mentioned earlier, community management requires collecting private information from members about their energy consumption. This activity,

[3]This is an assumption of our setup, to guarantee to the community members a "turnkey" contract when inside the community.

[4]$r(1) < 1$ implies that even if the community is "fully covered", the consumer's energy demand cannot be entirely met by the internal production of the community. Recent literature on operating photovoltaic plants combined with storage systems for instance, confirms that the self-consumption curve is increasing in the capacity produced and, then, to the community, with a slight tendency to be convex due to synchronization between production and consumption profiles generated within the community (Huld et al., 2014; Zatti et al., 2021).

[5]In other words, $r = \frac{r(m)}{m}$ is the self consumption rate as the percentage of the energy produced by the community that is consumed by its members.

[6]If $x \to \underline{x}$ the community is "fully covered", i.e. $m = 1$

carried out by the aggregator, is essential for the efficient management of the community, but it also allows the latter to know how energy is used, at what time, for what household appliances and for how long. This information can be a further source of revenue for the aggregator. He could make money by selling the collected information to companies that produce consumer goods, electronic equipment, or directly to companies that collect and process data.

We measure the level of detail of the collected information through the variable θ, distributed over the interval $[0, 1]$. A high value of θ means that very "private" information about the community members is collected, on the contrary a low θ implies that the aggregator learns only "basic" information.

We assume that each member suffers a nuisance cost from the misuse of this information, which can be interpreted as an increased risk of data breach incidents and/or perceived negative effects related to loss of personal privacy. We will refer to this as a "privacy cost" and measured by the function $g(\theta)$ with the properties that $g'(\theta) > 0$, $g''(\theta) \geq 0$ and $g(0) = 0$.[7] Denoting by p the energy price paid to the aggregator, the utility function of each member of the community is linearly formed by three elements, i.e.:

$$\begin{aligned} u(x, m, p, \theta) &= (x - p) q + (1 + \gamma) x r(m) - g(\theta), \\ &= (x - p) [1 - r(1 - F(x))] + (1 + \gamma) x r(1 - F(x)) - g(\theta) \end{aligned} \tag{4}$$

where $x - p$ is the net utility of the energy supplied by the aggregator in quantity q, $(1 + \gamma) x r(m)$ is the utility associated to the consumption of the energy produced within the community, and $g(\theta)$ is the privacy cost.

The aggregator The primary function of the aggregator is to oversee the energy generated by the renewable energy plants to ensure optimal consumption of energy within the community. This task is commissioned by the municipality in return for payment of a licence fee $w > 0$ per member.

The aggregator is the sole supplier of the energy q needed by the members to cover the demand that cannot be met by the own production of the community. For this energy, he sets the price p as a profit maximizer. [8] Yet, the efficient operation of the community requires the collection of information to increase, in turn, efficiency in energy consumption. The misuse of this information may generate additional revenues for the aggregator. Operationally, we assume that these revenues are linear on the level of information collected:

$$R(m, \theta) = mb\theta \tag{5}$$

where $b > 0$ indicates the unit price of personal data. The profit function of the aggregator is then:

$$\pi(p, m, w, \theta) = m [pq + b\theta - w]. \tag{6}$$

[7] The term $g(0) = 0$ should be interpreted as the case where the aggregator does not use the collected information inappropriately.

[8] The aggregator can produce energy with its own plants (e.g., photovoltaic or through other renewable sources), or participate in energy market auctions to obtain advantageous prices. In either case, for sake of simplicity, p can be seen as net of the the supply cost. Adding a supply cost would strengthen our findings without changing the results.

3 Equilibrium analysis

In this section we focus on the functioning of the community after the investment has been made, leaving to the next section the deepening of the investment decision, and in relation to a given data collection policy θ. For both equilibria we determine the optimal participation strategy and the community benefit.

3.1 Private governance

The optimization problem of the aggregator is:

$$\max_{p} \pi\left(p, m, w, \theta\right) \tag{7}$$

$$\text{s.t.} \quad u\left(x, m, p, \theta\right) \geq \overline{u} \tag{8}$$

where m is given by (3). Consumers not involved in the community meet their entire energy demand with a standard contract, signed with the local energy supplier. The cost of this contract is such that $\overline{u} = 0$. Thus, the Individual Rationality (IR) constraint is satisfied by setting the price p equal to:

$$p\left(x, m, \theta\right) = \frac{x\left(1 + \gamma r m\right) - g\left(\theta\right)}{1 - rm}, \tag{9}$$

where x is the cut-off type of a consumer who is indifferent between being part of the community or not. This case of private equilibrium is described using the subscript P. It is worth to notice that the aggregator is able to capture the overvaluation consumers make of the self-produced energy by increasing the price of the energy he sells. Substituting (9) in (7) and maximizing with respect to x we obtain the following proposition:

Lemma 1 (Profit-maximizing cutoff)

$$\underbrace{\left[x_P - \frac{1 - F\left(x_P\right)}{f\left(x_P\right)}\right]\left[1 + \gamma r\left(1 - F\left(x_P\right)\right)\right]}_{\text{Virtual valuation}} + \underbrace{\gamma r\left(1 - F\left(x_P\right)\right) x_P}_{\text{Overvaluation}} + \underbrace{b\theta}_{\substack{\text{Marginal revenue} \\ \text{from data sales}}} = \underbrace{w + g\left(\theta\right)}_{\substack{\text{Marginal} \\ \text{cost}}} \tag{10}$$

The formal proofs of all the results are relegated to the Appendix.

The marginal revenue (the left hand side of eq. 10) is composed by: the consumer's virtual assessment of purchased energy plus the premium the aggregator gets because of the overvaluation of energy by the consumers $\gamma r\left(1 - F\left(x_P\right)\right) x_P$, plus the marginal revenue from selling the collected information. The marginal cost (the right-hand side of eq. 10) is composed by the fee paid to the municipality and the privacy cost. Recalling from (3) that the size of the community under the private governance is $m_P = 1 - F\left(x_P\right)$ we can prove the following comparative statics:

Proposition 1 (Community size under private governance)

1. *An increase in the overvaluation parameter γ leads to a decrease in the size of the community:*

$$\frac{\partial m_P}{\partial \gamma} < 0. \tag{11}$$

2. *An increase in the efficiency parameter r, decreases the community size.*

$$\frac{\partial m_P}{\partial r} < 0. \tag{12}$$

3. *An an increase in the fee w paid by the aggregator to the municipality results in a smaller community size:*

$$\frac{\partial m_P}{\partial w} < 0. \tag{13}$$

4. *An increase in the price of data b widens the community size m:*

$$\frac{\partial m_P}{\partial b} > 0. \tag{14}$$

The results of comparative statics are as expected. In particular, as both the parameters γ and r increase the aggregator selling price p, they contribute to reduce the optimal size of the community, while an increase in the fee paid by the aggregator to the municipality for operating the system reduces the optimal size of the community. Regarding the collection of information we can prove that:

Corollary 1 (Community size and information collection)
If $b > g'(\theta)$, the more detailed is the information collected by the aggregator the greater is the size of the community, i.e.:

$$\frac{\partial m_P}{\partial \theta} > 0 \tag{15}$$

The effect of increasing the level of detail of the information collected depends on the relationship between the marginal cost of privacy and the price paid to the aggregator for the data collected. As data becomes more valuable to the digital marketplace and its price rises, the aggregator increases both its collection and the optimal community size thereby increasing profits (i.e. $\frac{\partial \pi}{\partial \theta} > 0$).
By (4), (9) and (10), the overall utility of the community, expressed as a function of the optimal willingness to pay x_p, is:

$$U(x_P) = \int_{x_p}^{\bar{x}} u(x, x_P)\, dF(x) = [1 + \gamma r (1 - F(x_P))] \int_{x_P}^{\bar{x}} (x - x_P)\, dF(x)\,. \tag{16}$$

where the term $\int_{x_P}^{\bar{x}} (x - x_P)\, dF(x)$ captures the total utility of all community members per unit of energy consumed. When the optimal cut off equals the upper-bound, i.e. $x_P = \overline{x}$, the community is empty ($m_P = 0$) and the utility is nil ($U(\overline{x}) = 0$). On the contrary, when $x_P = \underline{x}$, i.e. $m = 1$, we total utility is $U(\underline{x}) = (1 + \gamma r)(\lambda - \underline{x}) > 0$, expressing the utility of a complete community. Furthermore, it is easy to show that:

Corollary 2 (The utility of the community)

The utility of the community increases as the number of members increases:

$$\frac{dU(x_P)}{dx_P} < 0 \rightarrow \frac{dU(m_P)}{dm_P} > 0. \tag{17}$$

In other words, the benefit of increased self-consumption generated by a larger community more than balances the price increase that the aggregator will charge for residual energy.

3.2 Public governance

The public governance regime is the one in which the municipality retains control throughout the project. Under this alternative set up, we show that the optimal equilibrium is characterized by a larger participation and more self-consumption. To preserve the comparison with the private governance case, we maintain the symmetry assuming that the municipality retains also in this case a share w for the management of the community and the behavior of the public utility supervising the community is the same as well.[9]

The optimization problem of the municipality is determining the social cutoff x_W, where the subscript W stands for 'welfare', such that all consumers whose valuation equals or exceeds such a threshold, participates in the community, i.e.:

$$\max_x V(x, m, \theta), \tag{18}$$

where the social value of the community $V(x, m, \theta)$ is:

$$V(x, m, \theta) = \int_x^{\bar{x}} [y(1 - rm) + y(1 + \gamma)rm]\, dF(y) + m[b\theta - w - g(\theta)]. \tag{19}$$

The first term on the right-hand side of (19) captures the total utility of the members of the community. The second term collects revenue from the sale of data net of community management and privacy costs. By maximizing with respect to x we obtain:

Lemma 2 (Optimal cutoff with public governance)

$$\underbrace{x_W[1 + \gamma r(1 - F(x_W))]}_{\text{Energy valuation}} + \underbrace{b\theta}_{\text{Marginal revenue}} = \underbrace{w + g(\theta)}_{\text{Marginal Cost}}, \tag{20}$$

The social optimal size of the energy community is given by the equality of social marginal revenue (left hand side of eq. 20) and social marginal cost (right hand side of eq. 20).

The comparison between (11)) and (20) shows that the marginal cost is the same in the two cases while the marginal revenue differs. This implies that the two cutoffs are different, and consequently, the sizes of the communities differ, too. In Section 5 we will study the sign of this difference.

[9] We take care in Section 5 of the case where this quota differs from the one paid under the private governance context.

Proposition 2 (Community Size under Public Governance.)

Substituting (20) in (19) we can write the social value of the community as:

$$V(x_W) = U(x_W) - \int_{x_W}^{\bar{x}} \gamma r x \left[F(x) - F(x_W)\right] dF(x) \tag{21}$$

where the second term on the right hand side is negative. That is, $V(\bar{x}) = 0$ and $V(\underline{x}) < U(\underline{x}) = (1+\gamma r)(\lambda - \underline{x})$.

4 Establishment of the community

The investment in the infrastructure needed for community energy production is borne by the municipality. For each member of the community the investment cost paid is I. Yet, to reflect the recent trend of a gradual reduction in costs for both renewables' plants (such as photovoltaic panels and energy storage batteries), we assume that the cost evolves over time according a Geometric Brownian Motion (GBM) with a negative drift $\eta_t < 0$, i.e.:

$$dI_t = \eta I_t dt + \sigma I_t dB_t \qquad \text{and} \qquad I_{t=0} = I_0 \tag{22}$$

where σ is the instantaneous volatility and dB_t is the increment of a standard Brownian motion with $\mathbb{E}[dB_t] = 0$ and $\mathbb{E}\left[dB_t^2\right] = dt$.

The goal of the municipality is to identify the optimal time for investment to maximize the discounted present value of the utility of community members. Following the set up provided in previous sections, we first consider the investment decision when the community is under the private management and then in the public one.

Consider first the case where the community is managed by the private aggregator. For simplicity, we assume that both the price of energy p and the licence fee w, once stipulated at the set up of the community, remain constant over time.[10] Defining ρI^P as the annualized cost that induces the municipality to invest (where ρ is the discount factor), this is given by the solution to the following problem:

$$O_P(I_0, m_P) = \max_{I_P} \left(\frac{I_0}{I_P}\right)^{\beta} \left[U(m_P) + m_P(w - \rho I_P)\right], \tag{23}$$

where $\left(\frac{I_0}{I_P}\right)^{\beta} = \mathbb{E}_0\left(e^{-\rho \tau_P}\right)$ is the expected discount factor with $\beta < 0$ as the negative root of the characteristic equation $\left(\sigma^2/2\right) y(y-1) - \mu y - \rho = 0$.[11] Starting from $I_0 \leq I_P$, the municipality invests when the annualized investment cost ρI_t decreases to ρI_P. That is:

[10]Fixed energy prices are one of the reasons why households are interested in joining the community: the stable price reduces the risks associated with future market fluctuations, and this is perceived positively by risk averse participants in particular. As mentioned before, long terms contracts are also needed in the community framework to guarantee the presence of the participants over time.

[11]Formally the expected discount factor $\left(\frac{I_0}{I_P}\right)^{\beta}$ can be determined by using dynamic programming on $\mathbb{E}_0\left(e^{-\rho\tau_P}\right)$, where the investment time is $\tau_P = \inf\{t \geq 0 \mid I_t = I_P\}$ (see, *e.g.*, Dixit and Pindyck (1994), pp. 315-316).

Proposition 3 **(Optimal investment under private governance)**

$$\rho I_P = \kappa \left[\frac{U(m_P)}{m_P} + w \right], \tag{24}$$

where $\kappa = \frac{\beta}{\beta-1} < 1$ *is the option value factor, which takes into account the uncertainty in costs and the irreversibility of the decision.*

Similarly, when the community is run by the public utility the optimal investment trigger ρI^W is given by the solution to the following problem:

$$O_W(I_0, m_W) = \max_{I_W} \left(\frac{I_0}{I_W} \right)^{\beta} [V(m_W) + m_W (w - \rho I_W)]. \tag{25}$$

Again, assuming that the current cost I_0 is sufficiently high to deem immediate investment sub-optimal, we obtain:

Proposition 4 **(Optimal investment under public governance)**

$$\rho I_W = \kappa \left[\frac{V(m_W)}{m_W} + w \right] \tag{26}$$

By simple algebra the trigger (26)) can be rewritten as:

$$\rho I_W = \kappa \left\{ \left(\frac{U(m_W)}{m_W} + w \right) - \left(\frac{\int_{x_W}^{\bar{x}} \gamma r x \left[F(x) - F(x_W) \right] dF(x)}{m_W} \right) \right\}, \tag{27}$$

where the first term of the right hand side. is the investment trigger when the community is run by the aggregator evaluated at the social size m_W.

In the following sections we provide the welfare analysis, a numerical example and then discuss policy implications.

5 Welfare analysis

Let us now compare the two regimes. We do this allowing the aggregator and the public utility to choose the optimal data collection which, in both cases, is given by $b = g'(\theta)$. The following proposition characterizes the main differences.

Proposition 5 (Comparison between private and public governance)

1. *the size of the community is smaller when it is run by the aggregator:*

$$m_P < m_W; \tag{28}$$

2. *the community utility is higher when it is managed by the aggregator, i.e.* $U(m_P) > V(m_W)$*, if* $m_P > \tilde{m}$ *where* $\tilde{m} = 1 - F(\tilde{x})$ *is given by:*

$$U(\tilde{m}) = V(m_W); \tag{29}$$

   and $U(m_P) < V(m_W)$ *otherwise.*

3. *the municipality invests sooner if community management will be assigned to the aggregator*

$$I_P > I_W. \tag{30}$$

When the community is funded by the municipality but managed by a profit-maximizing aggregator the size turns out to be smaller. The aggregator maximizes profits with a smaller community as it is able to extract extra rents from consumers due to the fact that they value self-generated energy more than purchased energy. However, despite a smaller size, the community is better off than public governance in the other two dimensions: a higher level of member utility when the gap $m_W - m_P$ is not too high and anticipation of starting. We can summarize this result by comparing (23) and (25). Substituting (24) and (26) into their respective equations, we can represent the difference as:

$$O_P - O_W = \psi \left[m_P (I_P)^{1-\beta} - m_W (I_W)^{1-\beta} \right], \tag{31}$$

where $\psi = (I_0)^{\beta} (\kappa^{-1} - 1)\rho > 0$.

If we take public governance case as a benchmark, we can ask for interventions that could bring private management into line with public management. From (31) it is immediately clear that this is always the case if it is possible to obtain $\Delta m = m_W - m_P = 0$ and $\Delta I = I_W - I_P = 0$. However, this is not an easy task because interventions have controversial effects on the three dimensions highlighted by the proposition.

5.1 Numerical example

Let us explore some options that can be adopted to align the private governance framework with the public one. First, the municipality may require the aggregator to set the size of the community at the socially desirable size m_P. In this case the difference between $U(x_P)$ and $U(x_W)$ increases even further, consequently, the investment trigger also shifts upwards (i.e. $\rho I_P' > \rho I_P$). Secondly, the municipality can incentivize the aggregator by setting a lower fee $w' < w$. This leads to an increase in m^P, but also to a decrease in the revenue received by the municipality from the aggregator, resulting in an increase in ΔI.

Furthermore, the aggregator may be required to share a portion of the total investment cost, i.e. αI, reducing the public financial effort to $(1-\alpha) I$. In this case, the size of the community chosen by the aggregator decreases, i.e. $m_P' < m_P$, without any positive certain effect on the difference $O_P - O_W$.

Finally, we consider the case where there is no fee when the community is managed by the municipality, i.e., $w_W = 0$ and no information is collected from members $\theta_W = 0$ under public governance. The municipality's objective is to reach the maximum size of the community, thus $m_W = 1$. We illustrate this case by providing a straightforward parametric example (details in Appendix 6). In this example, we set the private fee $w_P \in (0, \bar{w}_P]$, the price paid by third parties for consumers' data b equal to 1 and the privacy cost $g(\theta) = \frac{2}{3}\theta^{3/2}$, so that the maximum level of information is collected, i.e. $\theta_P = 1$. Furthermore, x is uniformly distributed on $[0, 1]$.[12]

Under this framework, the condition ensuring $x_P \geq x_W$ is:

$$w_P \leq \left(\frac{2}{3} - \gamma r\right) \tag{32}$$

where $\gamma r \in [0, 0.75]$ and $\bar{w}_M = \frac{8}{3}$. Consistent with the results in Proposition 1, an increase in γ and/or r requires a lower fee in the private equilibrium. Notice that $m_P = 1$ when $w_P = \frac{2}{3} - \gamma r$.

Let us now turn to the difference in investment timing. From (24) and (26), the investment trigger under private governance is higher or equal to the one under public governance when:

$$\kappa^{-1}\rho(I_P - I_W) = \frac{U(x_P)}{m_P} + w_P - \frac{V(m_W)}{m_W} - w_W \geq 0. \tag{33}$$

By setting $x_W = 0$ (i.e. $m_W = 1$), and $w_W = 0$, and asking the private aggregator to pay the fee w_P given by (32), condition (33) reduces to:

$$\kappa^{-1}(\rho I_P - \rho I_W) = \frac{2}{3}(1 - 2\gamma r) \tag{34}$$

Thus, $m_P = 1$ implies $O_P - O_W \geq 0$ if $\gamma \leq \frac{1}{2r}$ and negative otherwise.

This outcome provides interesting information. The municipality may aim for maximum community participation ($m_P = 1$) under the aggregator's management, while prohibiting data collection and waiving the license fee ($\theta_W = 0$ and $w_W = 0$). This approach could be justified, as the municipality itself is promoting the project. In such a scenario, it is always optimal to involve a private aggregator when the community members' environmental preferences are not particularly strong, i.e. γ is not so high. In other words, when agents do not have a very high commitment

[12] The aggregator maximizes profits by choosing θ to equal the marginal revenue with marginal cost $b = g'(\theta)$

in consuming green energy, entrusting the project to a private aggregator is the best choice since the externality generated by γ is not sufficient to ensure that the profit of the aggregator is so high while reducing the community size m_P. Conversely, i.e. γ high, municipality's optimal choice is to retain public control of the community.

5.2 Policy implications

The proposed analysis has identified several key areas that need to be regulated in order to ensure the unimpeded development of energy communities.

Starting from the numerical example and the comparison between the two possible types of governance, we show how environmental awareness, represented in this model by the value consumers assign to self-produced energy (through the parameter γ), has an impact on determining which type of governance is optimal.

If environmental awareness is not particularly high and the municipality's goal is to expand the community as much as possible, then the best solution is to entrust governance to the private aggregator, since he will not be able to rely solely on externalities to generate positive profits. This holds true in the absence of fees to be paid to the municipality and without the use of citizens' personal data. Conversely, when environmental awareness is very high, it is preferable for the municipality to manage the community itself since the Aggregator would set a smaller community thanks to the extraction of higher value from γ.

This finding is particularly relevant, as it illustrates how the optimal design of such initiatives depends on the specific contextual environment in which they are implemented. From a policy perspective, it suggests that welfare improvements can be achieved through the adoption of locally tailored strategies. In addition, the result conveys a second equally important implication: policies aimed at improving the environmental awareness of citizens, when effective, can influence the outcomes of local investment strategies (in this context, the development of energy communities and the corresponding levels of citizen participation). Together, these insights highlight the cyclical nature of policy effectiveness, underscoring the importance of ongoing evaluation and monitoring processes.

Linked to consumers' attitudes and legal issues, our work also concerns information management and data use freedom: in our model, the potential misuse of personal data is accounted as a cost, and this affects the willingness to participate in the community.

This issue has been significant in many countries, resulting in the introduction of data protection legislation. However, what needs consideration is not only data protection from a "static" perspective but also its consequences for consumer protection. When consumers consent to data processing, privacy regulations may be complied with, but the economic implications of this choice are often overlooked. Therefore, it is necessary to work from a contractual standpoint to protect participants and regulate market powers of various players.[13]

Policies concerning data security and protection are those that most significantly impact our framework, as privacy costs are decisive in the decision to participate in the community. Even the mere perception, and not just the real danger, that consumers' data is not protected affects the decision to join or not join the energy community: for this

[13] This need is motivated also by the observation that data collected from individuals might have multiple uses nowadays. For further discussion, see Bergemann et al. (2022) on the social and economic dimension of data collected from individuals.

reason, the role of the regulator is particularly relevant both in terms of defining the rules and ensuring their effective compliance. Public management may restrict data collection for ethical reasons, while private management requires careful regulation of data usage and privacy costs.

Remaining within the domain of consumer protection, our analysis is based on a strong assumption regarding the nature of participation in the energy community, specifically, that it involves a "turn-key" contract for energy supply. We not only assume that the community can never fully meet its energy demand through self-consumption alone, but we also posit that the shortfall is supplied by the operator, at a price that maximizes profit (in the case of a private operator). In the model, this is justified by the assumption that consumers value the stability of a fixed price over the uncertainty associated with variable market prices, a preference that becomes even more pronounced under conditions of macroeconomic instability. In addition, the share of energy that must be purchased externally by the community is assumed to be marginal. However, this solution is highly restrictive and limits consumer choice, as consumers are typically free to select their energy provider, just as they are free to join or leave the energy community. Nonetheless, regulators must be aware that such freedom undermines the stability of investments and, consequently, may deter private operators from participating in energy community projects.

Our discussion moves to the decision of the municipality to establish and finance an energy community, which is given for granted in our framework. In this sense, we are assuming that the municipality can be a good promoter for the investment, but not necessarily the best manager. We showed that public governance of energy communities tends to result in bigger community sizes, including also people who value relatively their environmental impact: in this case, the utility for the community is lower if compared to the private governance, and the investment is done slower. Vice versa, the private governance leads to a faster investment in a smaller, well-motivated community: in this case, the utility for the community is higher. In this case, it is necessary for the municipality to balance expectations about the size of the community with the need to invest in a reasonable time-frame. A new hypothesis with multiple (modular) communities could also be considered as a strategy for public authority, allowing for the inclusion of different population strata (characterized by different sensibilities towards the environment) step by step. Another focus is therefore investment timing. Following the principle that the sooner the better, we face a scenario in which more local public authorities decide to complete the physical construction phase of energy communities independently. How and to whom to delegate the management phase is a decision that follows the investment and this choice impacts both the size of the community and the overall well-being of its members.

In practical experience, delayed investment could lead to loss of investment opportunity due to excessive waiting by potential members, technological obsolescence, and the presence of competitors offering similar services in the market. Central government interventions might be a solution to help redistribution,for example, taxing revenue from data sales and transferring funds to municipalities. This can help offset privacy costs for members while encouraging earlier investments.

As a final consideration, it is necessary to remember that both technological and organizational progress can undergo particularly rapid evolutions, leading, for example, to a decrease in the management costs of communities. This type of evolution implies that policies must also be re-adapted.

6 Conclusions

The environmental and digital transformations are progressing along separate but interrelated paths, with the latter acting as a crucial tool to optimize resource intensity and move towards less polluting solutions.

Within the domain of the energy transition, as part of the ecological one, digital innovation provides technological solutions facilitating the phase-out of fossil fuels in the energy sector and promoting the adoption of renewable energy sources, while also favoring proximity in production and consumption.

Among the several strategies designed by policymakers in the realm of this transition, the creation of energy communities represents a complex socioeconomic, environmental, and technological challenge identified in creating local systems able to support the consumption of energy produced from renewable sources cooperatively within a close geographical area. Such a transformation involves different actors, ranging from energy consumers, local institutions/regulators as well as energy and technology providers, and needs to account for investments' choices, and constraints, together with individual preferences towards green energy benefits and uncertainties.

Our paper presents a comprehensive economic modeling framework that incorporates all these elements. It combines theoretical microeconomic modeling under uncertainty (Dixit and Pindyck, 1994) within the realm of energy economics with the application of information theory to digital platforms (Bergemann et al., 2022); environmental sensitiveness is also included as determinant of consumers' preferences. This framework is set within a context characterized by public-private interactions (Schmitz, 2015) and integrates the benefits and drawbacks associated with the adoption of information and communication technology as a means of optimizing and promoting the consumption of renewable energy. It is worth noting that the issue of the so-called unbundling regulation is underlying what has been described regarding the growing importance of information in the relationships between different market players.

From our analysis several policy insights arise, ranging from the relevance of the community governance choice and the growing role of digitalization as a tool to favor and optimize renewable energy consumption within the shortest geographical distance. Our discussion focuses specifically on some points that we believe must be considered in the policy debate regarding the decentralization, and digitalization as well, of the energy markets, which in turn finds in the energy communities framework one of its main instruments.

Moreover, the influence of environmental preferences on consumer choices and the utility derived from investments underscores the need for differentiated investment policies, complemented by education and awareness initiatives to enhance environmental consciousness.

Future extensions of the work should take into account differences between consumers, considering possible heterogeneity in attitudes to sharing personal information, while also linking them to concepts such as energy access and energy poverty. The distribution of costs and benefits is not modelled according to the characteristics of the agents, whereas other works do. These approaches contribute to a rigorous discussion about the promotion and the establishment of the energy communities, beyond ideological positions.

Acknowledgments. Dirk Bergemann acknowledges the financial support of Fondazione Eni Enrico Mattei, Italy; Marina Bertolini acknowledges the financial support of European Union - Next Generation EU - Research Project

GRINS - Growing Resilient, INclusive and Sustainable. The National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 funded from the European Union - NextGenerationEU - Spoke n. 6 and of the Levi Cases Centre for Energy Economics and Technology of the University of Padova (under the project: "The future of energy: institutions, regulation and enabling factors" and "INCITE"); Marta Castellini acknowledges the financial support of European Union - Next Generation EU - Research Project GRINS - Growing Resilient, INclusive and Sustainable. The National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 funded from the European Union - NextGenerationEU - Spoke n. 6 and Fondazione Eni Enrico Mattei, Italy Michele Moretto acknowledges the financial support of Fondazione Cariparo, Italy, within the ProTECTO Project (grant n. 59586); Sergio Vergalli acknowledges the financial support of Fondazione Eni Enrico Mattei, Italy.

Appendix

Proof of lemma 1

The aggregator's profit (6) expressed as a function of the willingness to pay x is:

$$\pi(x) = [1 - F(x)]\, x\, [1 + \gamma r(1 - F(x))] + [1 - F(x)]\, [b\theta - w - g(\theta)]\,. \tag{35}$$

The first order condition (FOC) gives :

$$\left[x - \frac{1 - F(x)}{f(x)}\right] [1 + \gamma r(1 - F(x))] + [1 - F(x)]\, x\gamma r + b\theta = w + g(\theta)\,. \tag{36}$$

The second order condition (SOC) is:

$$-1 + \frac{\partial\left[\frac{1-F(x)}{f(x)}\right]}{\partial x} [1 + \gamma r(1 - F(x))] + \gamma r f(x)\, x \left[2 - 3\frac{(1 - F(x))}{f(x)\, x}\right] \leq 0 \tag{37}$$

As $\frac{1-F(x)}{f(x)x}$ is decreasing in x, sufficient condition for (37) to hold is $f(\underline{x})\, \underline{x} \leq \frac{3}{2}$.

Proof of proposition 1 and corollary 1

The comparative statics with respect to w and b gives:

$$\frac{\partial x_P}{\partial w} = -\frac{1}{SOC} > 0, \qquad \frac{\partial x_P}{\partial b} = \frac{\theta}{SOC} < 0.$$

while concerning γ and r we get:

$$\frac{\partial x_P}{\partial \gamma} = -\frac{\left[x - \frac{1-F(x)}{f(x)}\right] [r(1 - F(x))] + [1 - F(x)]\, xr}{SOC} > 0 \tag{38}$$

$$\frac{\partial x_P}{\partial r} = -\frac{\left[x - \frac{1-F(x)}{f(x)}\right] [\gamma(1 - F(x))] + [1 - F(x)]\, x\gamma}{SOC} > 0 \tag{39}$$

Finally when considering detail in data collection, we have:

$$\frac{\partial x_P}{\partial \theta} = -\frac{b - g'(\theta)}{SOC} < 0 \quad if \quad b - g'(\theta) > 0. \tag{40}$$

Proof of corollary 2

The first derivative of $U\left(x^P\right)$ with respect to x_P gives:

$$\begin{aligned}\frac{\partial U(x_P)}{\partial x_P} &= -\gamma r f(x_P) \int_{x_P}^{\bar{x}} (x - x_P) dF(x) \\ &\quad - [1 + \gamma r(1 - F(x_P))]\, [1 - F(x_P)] \leq 0\end{aligned} \tag{41}$$

which is negative. That is $\frac{\partial U(m_P)}{\partial m_P} > 0$.

Proof of proposition 2

The social cutoff is given by:

$$\max_{x} \int_{x}^{\bar{x}} \left[y \left(1 - r \left(1 - F \left(x\right)\right)\right) + y(1+\gamma) r \left(1 - F \left(x\right)\right)\right] dF \left(y\right) + \left[1 - F \left(x\right)\right] \left[b\theta - w - g \left(\theta\right)\right]. \tag{42}$$

The first order condition is:

$$x \left[1 + \gamma r \left(1 - F \left(x\right)\right)\right] + b\theta = w + g \left(\theta\right). \tag{43}$$

The second order condition is:

$$-1 + \gamma r f \left(x\right) x \left[1 - \frac{\left(1 - F \left(x\right)\right)}{f \left(x\right) x}\right] < 0, \tag{44}$$

As $\frac{1-F(x)}{f(x)x}$ is decreasing in x, sufficient condition for the second order condition to hold is $f\left(\underline{x}\right)\underline{x} \leq 1 + \frac{1}{\gamma r}$ which, by the assumption $f\left(\underline{x}\right)\underline{x} \leq \frac{3}{2}$, is always satisfied as $\gamma r < 1$.

Proof of proposition 5

To assess whether the size of the community is greater in one of the two equilibria, we start by comparing the two first-order conditions described in (10) and (20). Let's define the private marginal benefit (PMB) and the social marginal benefit (SMB) respectively, as:

$$PMB = \left[x - \frac{1 - F\left(x\right)}{f\left(x\right)}\right]\left[1 + \gamma r \left(1 - F\left(x\right)\right)\right] + x\gamma r \left[1 - F\left(x\right)\right] + b\hat{\theta}, \tag{45}$$

$$SMB = x\left[1 + \gamma r \left(1 - F\left(x\right)\right)\right] + b\hat{\theta}, \tag{46}$$

and difference between the two benefits is:

$$PMB - SMB = -\frac{1 - F\left(x\right)}{f\left(x\right)}\left[1 + \gamma r \left(1 - F\left(x\right)\right)\right] - x < 0. \tag{47}$$

By the second order conditions (37) and (44), both the private marginal benefit (45) and the social marginal benefit (46) are increasing in x, while the private marginal cost and the social marginal cost are constant and equal to $w + g\left(\theta\right)$. Consequently, it follows that $x_P > x_W$ and then $m_P < m_W$.

In addition, as $U\left(x\right)$ is decreasing in x and $V\left(x_W\right) < U\left(x_W\right)$, we can have both $V\left(x_W\right) > U\left(x_P\right)$ and $V\left(x_W\right) < U\left(x_P\right)$. In particular $V\left(x_W\right) > U\left(x_P\right)$, if $x_P > \tilde{x}$ where $\tilde{x}$, is given by:

$$V\left(x_W\right) - U\left(\tilde{x}\right) = 0$$
$$U(x_W) - U\left(\tilde{x}\right) - \int_{x_W}^{\bar{x}} \gamma r x \left[F(x) - F(x_W)\right] dF(x) = 0$$

and $V\left(x_W\right) < U\left(x_P\right)$ otherwise. Put another way, as $U\left(m\right)$ is increasing in m, $V\left(m_W\right) > U\left(m_P\right)$ if $m_P < \tilde{m} = 1 - F(\tilde{x})$ and $V\left(m_W\right) < U\left(m_P\right)$ otherwise.

Finally, to prove that $I_P > I_W$ we need to show that $\frac{U(m_P)}{m_P} > \frac{V(m_W)}{m_W}$. From the above result it is easy to show that $\frac{U(\tilde{m})}{\tilde{m}} > \frac{V(m_W)}{m_W}$. Then if $m_P < \tilde{m}$ (i.e. $x_P > \tilde{x}$), the disequality $I_P > I_W$ is always satisfied.

Let consider now the case where $m_P > \tilde{m}$ (i.e, $x_P < \tilde{x}$), and assuming that there is a value $\check{m} > \tilde{m}$ such that:

$$\frac{U(\check{m})}{\check{m}} = \frac{V(m_W)}{m_W}$$

As $\frac{dV(m_W)}{dm_W} = 0$, the value $\check{m}$ exists only if the utility $U(m)$ is concave, which implies that $\check{m} > m_W$, that contradicts the fact that $m_P < m_W$. Thus, we conclude that $I_P > I_W$ is always satisifed.

Numerical example

The optimal cutoff identified by the aggregator x_P is given by the solution of the following equation:

$$3\gamma r (x_P)^2 - 2(1+2\gamma r) x_P + \left(\gamma r - \frac{2}{3}\right) + w_P = 0.$$

$\bar{w}_P \geq \frac{8}{3}$ the optimal cutoff is:

$$x_P = \frac{(1+2\gamma r) - \sqrt{(1+2\gamma r)^2 - 3\gamma r\left[\left(\gamma r - \frac{2}{3}\right) + w_P\right]}}{3\gamma r} < 1 \tag{A}$$

On the contrary, the cutoff type in the public equilibrium is simple equal to $x_W = 0$. By (A), the condition assuring $x_P \geq x_W$ is:

$$\mathbf{w}_P \leq \left(\frac{2}{3} - \gamma r\right) \tag{B}$$

For the investment timing we know that the difference of optimal triggers is:

$$\kappa^{-1}\rho(I_P - I_W) = \frac{U(m_P)}{m_P} + w_P - \frac{V(m_W)}{m_W} - w_W. \tag{48}$$

Fixing $x_P = x_W$ (i.e. $m_P = m_W$), the above difference reduces to:

$$\kappa^{-1}(\rho I_P - \rho I_W) = w_P - w_W - \frac{\int_{x_W}^{\overline{x}} \gamma r x \left[F(x) - F(x_W)\right] dF(x)}{1 - F(x_W)}, \tag{49}$$

Further, setting $x_W = 0$ (i.e. $m_W = 1$), and $w_W = 0$, by simple algebra, we obtain:

$$\kappa^{-1}(\rho I_P - \rho I_W) = w_P - \gamma r \int_0^1 x^2 dx = w_P - \frac{\gamma r}{3}, \tag{50}$$

Substituting (B) yields:

$$\kappa^{-1}(\rho I_P - \rho I_W) = \frac{2}{3}(1 - 2\gamma r).$$

References

Acquisti, A., Taylor, C., and Wagman, L. (2016). The economics of privacy. *Journal of economic Literature*, 54(2):442–492. 14

Agostini, M., Bertolini, M., Coppo, M., and Fontini, F. (2021). The participation of small-scale variable distributed renewable energy sources to the balancing services market. *Energy Economics*, 97:105208. 14

Andreolli, F., D'Alpaos, C., and Moretto, M. (2022). Valuing investments in domestic pv battery systems under uncertainty. *Energy Economics*, 106:105721. 14

Bennett, J. and Iossa, E. (2006). Building and managing facilities for public services. *Journal of Public Economics*, 90(10):2143–2160. 14

Bergemann, D., Bonatti, A., and Gan, T. (2022). The economics of social data. *The RAND Journal of Economics*, 53(2):263–296. 14, 13, 6

Bertolini, M., D'Alpaos, C., and Moretto, M. (2018). Do smart grids boost investments in domestic pv plants? evidence from the italian electricity market. *Energy*, 149:890–902. 14

Bottom, W. P., Holloway, J., Miller, G. J., Mislin, A., and Whitford, A. (2006). Building a pathway to cooperation: Negotiation and social exchange between principal and agent. *Administrative Science Quarterly*, 51(1):29–58. 14

Brown, D., Hall, S., and Davis, M. E. (2020). What is prosumerism for? exploring the normative dimensions of decentralised energy transitions. *Energy Research & Social Science*, 66:101475. 11

Carbonara, N., Costantino, N., and Pellegrino, R. (2014). Concession period for ppps: A winwin model for a fair risk sharing. *International Journal of Project Management*, 32(7):1223–1232. 14

Carbonara, N. and Pellegrino, R. (2020). The role of public private partnerships in fostering innovation. *Construction management and economics*, 38(2):140–156. 14

Castellini, M., Di Corato, L., Moretto, M., and Vergalli, S. (2021a). Energy exchange among heterogeneous prosumers under price uncertainty. *Energy Economics*, 104:105647. 14

Castellini, M., Menoncin, F., Moretto, M., and Vergalli, S. (2021b). Photovoltaic smart grids in the prosumers investment decisions: a real option model. *Journal of Economic Dynamics and Control*, 126:103988. 14

Choi, J. P., Jeon, D.-S., and Kim, B.-C. (2019). Privacy and personal data collection with information externalities. *Journal of Public Economics*, 173:113–124. 14

Clò, S., Iannucci, G., and Tampieri, A. (2025). Dynamic choice of renewable energy communities: Bottom-up vs top-down organisation. *Mathematical Social Sciences*, page 102412. 14

Conrad, K. (2005). Price competition and product differentiation when consumers care for the environment. *Environmental and Resource Economics*, 31:1–19. Accepted 18 November 2004. 14

De Wildt, T., Chappin, E., Van de Kaa, G., Herder, P., and Van de Poel, I. (2019). Conflicting values in the smart electricity grid a comprehensive overview. *Renewable and Sustainable Energy Reviews*, 111:184–196. 14

Dixit, R. K. and Pindyck, R. S. (1994). *Investment under uncertainty*. Princeton university press. 11, 6

EU (2019). *Clean energy for all Europeans. European Commission and Directorate-General for Energy*. Publications Office. 13

Galperti, S., Levkun, A., and Perego, J. (2023). The Value of Data Records. *The Review of Economic Studies*, 91(2):1007–1038. 14

Han, X., Khouja, M., and Liu, X. (2023). A dynamic model considering consumer green awareness and environmental subsidy. *International Journal of Production Economics*, 260:108840. 14

Hao, X., Miao, E., Sun, Q., Li, K., Wen, S., and Wu, H. (2025). When climate policy's up in the air: How digital technology impacts corporate energy intensity. *Energy Economics*, 144:108311. 14

Houde, S. and Myers, E. (2021). Are consumers attentive to local energy costs? evidence from the appliance market. *Journal of Public Economics*, 201:104480. 14

Huld, T., Ruf, H., Heilscher, G., et al. (2014). Self-consumption of electricity by households, effects of pv system size and battery storage. *Proceedings of the 29th EUPVSC, Amsterdam.* 4

Laffont, J.-J., Tirole, J., Idei, G., and Ceras (1993). Cartelization by regulation. *Journal of Regulatory Economics*, 5(2):111–130. 1

Li, Y., Li, J., He, J., and Zhang, S. (2021). The real-time pricing optimization model of smart grid based on the utility function of the logistic function. *Energy*, 224:120172. 14

Loisel, R. and Lemiale, L. (2023). Welfare implications of renewable energy communities. individual versus collective approach. *HAL open science - open archive.* 14

Luzzati, T., Mura, E., Pellegrini, L., Raugi, M., Salvati, N., Schito, E., Scipioni, S., Testi, D., and Zerbino, P. (2024). Are energy community members more flexible than individual prosumers? evidence from a serious game. *Journal of Cleaner Production*, 444:141114. 14

López, J. C., Pappu, A., Hoogsteen, G., Hurink, J. L., and Rider, M. J. (2024). Distributed management of energy communities using stochastic profile steering. *International Journal of Electrical Power & Energy Systems*, 158:109973. 11

Mansoor, M. and Paul, J. (2022). Impact of energy efficiency-based ict adoptions on prosumers and consumers. *Journal of Cleaner Production*, 331:130008. 14

Moore, M. A., Boardman, A. E., and Vining, A. R. (2017). Analyzing risk in ppp provision of utility services: A social welfare perspective. *Utilities Policy*, 48:210–218. 14

Petrucci, A., Ayevide, F. K., Buonomano, A., and Athienitis, A. (2023). Development of energy aggregators for virtual communities: The energy efficiency-flexibility nexus for demand response. *Renewable Energy*, 215:118975. 11

Rhodes, A. and Zhou, J. (2024). Personalization and privacy choice. *Cowles Foundation Discussion Paper*, CFDP 2388. 11

Schaefer, J. L., Mairesse Siluk, J. C., Stefan de Carvalho, P., Maria de Miranda Mota, C., Pinheiro, J. R., Nuno da Silva Faria, P., and Gouvea da Costa, S. E. (2023). A framework for diagnosis and management of development and implementation of cloud-based energy communities - energy cloud communities. *Energy*, 276:127420. 11

Schmitz, P. W. (2015). Government versus private ownership of public goods: The role of bargaining frictions. *Journal of Public Economics*, 132:23–31. 14, 6

Schrammel, J., Diamond, L. M., Fröhlich, P., Mor, G., and Cipriano, J. (2023). Influencing residential electricity consumption with tailored messages: Long-term usage patterns and effects on user experience. *Energy, Sustainability and Society*, 13(1):15. 14

Srithapon, C. and Månsson, D. (2023). Predictive control and coordination for energy community flexibility with electric vehicles, heat pumps and thermal energy storage. *Applied Energy*, 347:121500. 14

Takashima, R., Yagi, K., and Takamori, H. (2010). Government guarantees and risk sharing in publicprivate partnerships. *Review of Financial Economics*, 19(2):78–83. Project Finance. 14

Wörner, A., Tiefenbeck, V., Wortmann, F., Meeuw, A., Ableitner, L., Fleisch, E., and Azevedo, I. (2022). Bidding on a peer-to-peer energy market: An exploratory field study. *Information Systems Research*, 33(3):794–808. 14

Xu, Q., Zhong, M., and Li, X. (2022). How does digitalization affect energy? international evidence. *Energy Economics*, 107:105879. 14

Yang, C., Fu, Y., He, L., Jiang, Q., and Cui, Y. (2024). Real options analysis for regional investment decisions of household pv-ess in china. *Energy*, 293:130725. 14

Zatti, M., Moncecchi, M., Gabba, M., Chiesa, A., Bovera, F., and Merlo, M. (2021). Energy communities design optimization in the italian framework. *Applied Sciences*, 11(11):5218. 4

Zhang, Y., Qu, Y., Gao, L., Luan, T. H., Jolfaei, A., and Zheng, J. X. (2023). Privacy-preserving data analytics for smart decision-making energy systems in sustainable smart community. *Sustainable Energy Technologies and Assessments*, 57:103144. 11

Zheng, J. and Wang, X. (2021). Can mobile information communication technologies (icts) promote the development of renewables?-evidence from seven countries. *Energy Policy*, 149:112041. 14