Setting up an Energy Community under cost uncertainty

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Abstract

Our paper provides a theoretical real options framework for modeling prosumers' investment decisions in photovoltaic plants in a Smart Grid context, when P2P exchange is possible and the two prosumers can be organized in an energy community. We focus on the optimal size of their photovoltaic plants and on the self-consumption profiles the prosumers must comply with to assure the demand and supply matching in P2P exchange. The model was calibrated on the Northern Italy energy market. We investigate the investment decision under different prosumers' behaviors, taking into account all the possible combinations of their energy demand and supply. Our findings show that the existence of the energy community is not assured in all the cases we have focused on but depends on the shape and relationship between the supply and demand curves of the two prosumers. The best situation is when the two prosumers have an excess of supply and asymmetric and perfectly complementary demand curves. Sub-optimal cases occur when the P2P exchange and the sell to the national grid are exploited advantageously. This scenario is profitable if there is efficient cooperation between the two agents. Furthermore, prosumers invest in the highest capacity when they are characterized by different exchange P2P and self-consumption profiles, and they reach the maximum gain from the investment when the energy community is characterized by excess supply in exchange P2P.
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1 Introduction

The last decade has been characterized by the increasing use of renewable energy sources as alternative to fossil fuels. Such a process has been widely encouraged by policymakers to achieve decarbonization targets. In this context, both in Italy and in other EU countries, a number of distributed power plants have been installed, even though much effort is still required to achieve a sustainable energy future. [1]
Compared to fossil fuels, renewable energy sources are known to be beneficial in terms of environmental impact, but are often characterized by inflexible production compared to load curves. In particular, photovoltaic (PV, hereafter) production shows a certain variability depending on daily and seasonal solar irradiation, but, above all, its production is concentrated in certain daily time slots, leaving night-time demand unsupplied and showing problems in managing peak demand.
This makes challenging the management of the electricity grid (for instance in terms of inefficiency, congestion rents, power outages, etc.) which may benefit from the introduction of digitalization for becoming a *smarter* electricity grid[2]. This implies the innovation of the power system, a concept that has also been associated in the last years with the Smart Grids (SG, hereafter) which can be defined as "robust, self-healing networks that allow bidirectional propagation of energy and information within the utility grid".[3]
Such a technological transformation is characterized by three fundamental elements: i) the continuous integration of Distributed Energy Resources (DERs, hereafter), (Sousa et al. (2019); Bussar et al. (2016); Zhang et al. (2018)),[4]; ii) the massive introduction of Information and Communication Technology (ICT) devices (Saad al sumaiti et al., 2014); iii) the central role of the prosumers'[5] production and consumption choices (Luo et al. (2014); Sommerfeldt and Madani (2017); Espe et al. (2018); Zafar et al. (2018)).
The SG context allows and leads the players of the energy markets to adopt new behaviors. With reference in particular to traditional consumers, charac-

[1]International Renewable Energy Agency (IRENA) remarks, in its *Roadmap to 2050*, the importance to boost investments in clean energy technologies since still two-thirds of global greenhouse gas emissions stem from energy production and use.

[2]Campagna et al. (2020) describe the idea of the smart grids as "the merge of digital technology, DES and ICT for energy consumption optimization, which provides and enhances the traditional power grid in terms of flexibility, reliability and safety". Feng et al. (2016) remark the contribution of smart grids in "reducing power outage, lowering delivery costs, encouraging more energy conscious behaviors from consumers" as well as in the transition towards low-carbon economic growth. Moreno et al. (2017) describe in details the evolving landscape from conventional electricity systems to low-carbon smart grids, underlining the transition of distribution networks from passive structures to active systems and the evolution of end-users, which "will become active participants in system and market operation" as well as remarking the "opening up opportunities for aggregating and coordinating consumers and system needs".

[3]Smart Grid definition according EU. *Source* `https://ec.europa.eu/energy/en/topics/market-and-consumers/smart-grids-and-meters`

[4]e.g., from rooftop solar panels, storage and control devices

[5]Consumers who **pro**duce, con**sume** and share energy with other grid users.

terized by a passive behavior in buying and receiving energy from the grid, they gain the opportunity to become proactive in managing their consumption and production (Zafar et al., 2018), reducing their energy consumption costs, by self consuming the energy produced by their PV plants (Luthander et al. (2015); Masson et al. (2016)) as well as integrating effectively and efficiently into the electricity markets (Parag and Sovacool (2016)).[6]

Indeed, the EU's *Clean energy for all Europeans package* [7] has set a new legal framework for the internal energy market and particular attention has been devoted to the benefits of consumers, from both environmental and economic perspectives. The EU Directive 2018/2001[8] formally introduces the *renewables consumers* and sets the elements needed to ensure the spread of this status as much as possible.

As widely acknowledged by researchers in this field, the SG deployment, as well as its evolution, is also strictly related to the Peer-to-Peer (P2P, hereafter) energy trading concept and the development of energy communities (EC, hereafter).[9]

P2P represents "direct energy trading between peers, where energy from small-scale DERs in dwellings, offices, factories, etc, is traded among local energy prosumers and consumers" (Alam et al. (2017); Zhang et al. (2018))[10].

EC can involve groups of citizens, social entrepreneurs, public authorities and community organizations, participating directly in the energy transition by jointly investing in, producing, selling and distributing renewable energy[11]. The benefits in the energy markets arising for these new players range from their positive contribution in helping utilities to solve the energy management issues (Zafar et al. (2018)) as well as boosting investments in renewables' energy plants, thanks to the potential savings gained from cooperation in investment

[6]SG allow instantaneous interactions between agents and the grid: depending on its needs, the grid can send signals (through prices) to the agents, and agents can respond to those signals and obtain monetary gains as a counterpart. These two characteristics (self-consumption and possible return energy exchange with national grid) can add flexibility that, in turn, increases the value of the investment ((Bertolini et al., 2018), Castellini et al. (2020)).

[7]The EU's *Clean energy for all Europeans package* sets the new energy union strategy with eight legislative acts, where the main pillars are: energy performance in buildings, renewable energy, energy efficiency, governance regulation, electricity market design. The recast of EU Directive 2018/2001 aims "at keeping the EU a global leader in renewables" and sets new binding targets on renewable energy. Directive 2019/944 focuses on the new common rules for the internal market for electricity, where the "consumer is put at the center of the clean energy transition" and new rules are defined with the aim to enable their active participation in this process

[8]`https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A32018L2001`

[9](InterregEU (2018); Luo et al. (2014); Alam et al. (2017); Zafar et al. (2018); Zhang et al. (2018), (Sousa et al., 2019)).

[10]In detail: "peer-to-peer trading of renewable energy means the sale of renewable energy between market participants by means of a contract with pre-determined conditions governing the automated execution and settlement of the transaction, either directly between market participants or indirectly through a certified third-party market participant, such as an aggregator. The right to conduct peer-to-peer trading shall be without prejudice to the rights and obligations of the parties involved as final customers, producers, suppliers or aggregators" (EU (2018)).

[11]For futher defintions see EU (2019), Gui and MacGill (2018), van Summeren et al. (2020)

decisions and from the new flexibility in energy sourcing options. However, it is important to remark that their positive impact strictly depends on the adoption costs of the technology and the shape of the load (demand) electricity curve of the EC agents.
With reference to the effects of the direct exchange of energy between prosumers on SG deployment[12], researchers have analyzed and developed this topic with different perspectives and exploiting various approaches. A wide strand of this literature focuses on the study of the *Microgrids,* as communities of prosumers, with particular attention to their relationship with the electricity network, also deepening the prosumers' behavioral aspects. Significant importance has been also recognized by researchers to the need of a proper market design for the *prosumer era* (Parag and Sovacool (2016), Morstyn et al. (2018)). Several optimization techniques have been used to investigate prosumers' behaviors in self-consumption, exchange and investment choices (Zafar et al. (2018), Angelidakis and Chalkiadakis (2015), Razzaq et al. (2016)) and most of them focus on cost minimization (Liu et al., 2018). A different approach is provided instead by Gonzalez-Romera et al. (2019), in which the prosumers' benefit is determined minimizing the exchange of energy, instead of the energy cost and by Ghosh et al. (2018) where the price of exchanged P2P energy is defined with the aim of minimizing the consumption of conventional energy, even though prosumers' aim is to minimize their own payoffs.
Yet, there are still several interesting themes related to this topic that requires further development, such as: whether the additional flexibility provided by the exchange P2P may have value, how it could affect the investment decisions, and whether it may be supported by data. Some of the literature has tried to answer these questions: studying the possible combinations of agents in EC (Mishra et al. (2019)), or focusing on decentralized energy systems under different supply scenarios (Ecker et al. (2017)); Talavera et al. (2019), investigate the PV plant sizing problem under cost competitiveness and self-consumption maximization perspective whereas Jiménez-Castillo et al. (2019) exploit the NPV technique with a similar purpose but focusing also on economic profitability. To the best of our knowledge, problems concerning the possibility of matching load and supply curves in an uncertain environment, as well as in an EC framework, are yet to be investigated.

[12] Hernández-Callejo (2019)

This paper contributes to SG, EC research as well as to the real option literature in the energy field. [13]
Among these contributions, the closest to ours are: Bertolini et al. (2018) and Castellini et al. (2020) in the field of the optimal plant sizing and investment decisions under uncertainty; Luo et al. (2014) which focuses on the impact of cooperative energy trading on renewable energy utilization in a Microgrid context; Zhang et al. (2018) who investigate the feasibility of P2P energy trading with flexible demand; Gonzalez-Romera et al. (2019) where a minimization problem is developed with the aim to minimize the energy exchange in a framework of two prosumers households; Bellekom et al. (2016) who developed an agent-based model in a residential community context under different prosumption scenario. Our paper provides a theoretical framework for modeling the decision of two agents to invest in a photovoltaic (PV) plant, assuming they are integrated into an intelligent network (i.e. in a SG context), where exchange P2P is possible. Each agent can produce and consume the energy produced by the PV plant and clear any gap between its production and consumption by trading with both the national grid (N, hereafter) and the other agent. Uncertainty is taken into account by the dynamics of the price paid by the Transmission System Operator (TSO) to the prosumers for the energy sold to N, which is assumed to be stochastic. Each agent can buy energy from N paying a different stable price, while the price for the exchange of energy P2P (between the two prosumers) is modeled as a weighted average of the two prices for buying and selling energy from and to N. The investment decision is irreversible and taken cooperatively. Due to the irreversibility and high uncertainty over the demand evolution and market prices, the technological advances, and the ever changing regulatory environment (Schachter and Mancarella (2015); Schachter and Mancarella (2016); Cambini et al. (2016)), we implement a real option (RO) model to capture the value of managerial flexibility associated with the operation of the plant. In a two agents context, our purpose is to understand which characteristics of their supply-demand profiles favour energy exchange and are therefore compatible with the existence of an EC. Secondly, we determine the size of the PV plant which maximizes the joint benefit of the two agents and finally focus on the amount of energy exchange P2P and the self-consumption shares which allow prosumers to reach the highest saving.

[13] Mondol et al. (2009), Paetz et al. (2011), Kriett and Salani (2012), Pillai et al. (2014), Moreno et al. (2017), Farmanbar et al. (2019) and Campagna et al. (2020), among others, focuses on technological aspects of SG. Sun et al. (2013), Ciabattoni et al. (2014), Kästel and Gilroy-Scott (2015), Luthander et al. (2015), Ottesen et al. (2016), Bayod-Rújula et al. (2017) investigate the role of prosumers' behaviors, whereas Oren (2001), Salpakari and Lund (2016), Sezgen et al. (2007) study demand-side management and demand-response. With reference to exchange P2P, we recall, among others Angelidakis and Chalkiadakis (2015), Zafar et al. (2018), Ghosh et al. (2018), Liu et al. (2018), Gonzalez-Romera et al. (2019) and Hahnel et al. (2020); whereas in the EC field Mengelkamp et al. (2017), Razzaq et al. (2016), Moret and Pinson (2018),Gui and MacGill (2018), Espe et al. (2018), Morstyn et al. (2018), Sousa et al. (2019) and van Summeren et al. (2020). On the side of the real option literature, we complement the studies about the energy sector, among which Boomsma et al. (2012), Ceseña et al. (2013), Martinez-Cesena et al. (2013), Feng et al. (2016), Kozlova (2017), Tian et al. (2017),Schachter et al. (2016), Schachter and Mancarella (2016), Ioannou et al. (2017).

While the value of self-consumption and exchange (Bertolini et al. (2018), Castellini et al. (2020)) are two topics already studied in the literature, to the best of our knowledge, the conditions for the existence of an EC in a two-agent RO framework and the calculation of exchange energy rates are a novelty.
In order to do this, we investigate the investment decision under different prosumers' behaviors, taking into account all the possible combinations of energy demand and supply for the two agents. These are summarized in four scenarios we focus on. Scenario 1 refers to the case of excess of supply from both prosumers. Scenario 2 instead focuses on excess of demand. Scenario 3 shows the case where prosumer 1 needs not more than what the other prosumer could provide, while prosumer 2 needs more than the what prosumer 1 could provide. Scenario 4 instead analyzes the case in which prosumer 2 needs not more than what prosumer 1 could provide, while prosumer 1 needs more than what prosumer 2 could provide. Each scenario is therefore characterized by constraints in terms of energy exchange between the prosumers, leading to specific conditions under which the prosumers' self-consumption behaviors must comply to assure the feasibility of the scenario. In order to calculate the feasibility of our scenarios, we calibrate our model by using Italian energy market data. Model calibration is performed on a dataset built using Italian Zonal Electricity Prices to obtain the parameters of the stochastic price paid by the TSO to the prosumers for the energy sold to N. The cost of the investment is determined using the methodology of Bertolini et al. (2018) and other parameters refer to data provided by EUROSTAT, IRENA and International Energy Agency (IEA).
The main findings of our work are:

- in all four scenarios there are mathematically feasible conditions for having convenient energy exchange between agents and thus it is optimal to have an EC;
- among these mathematical conditions only some are feasible in reality, as only in some cases the solutions have economic significance and correspond to load and supply curves that can occur in the profile of an agent exchanging energy over the 24 hours;
- the situation which guarantee the existence of an EC and at the same time generate the maximum saving is one per scenario;
- among these, the profiles which guarantee the maximum benefit (NPV of the generated savings), are characterized by perfectly asymmetric and mutually complementary demand functions: agents produce, consume and exchange energy in such a way as to cover each other's opposite daytime demand functions. If they have an oversupply (scenario 1) they also sell some of their production to N in order to maximize the benefit. If they have excess demand (scenario 2), they sell nothing to N but cover all their daytime demand with their own production.
- The scenarios showing the lowest savings are the two asymmetric scenarios (3 and 4) with excess demand for one agent and excess supply for the

other one and viceversa. The combination which guarantees the existence of the EC is composed of an agent who produces to self-consume and sell, and a second agent who buys the surplus of the other agent and sells all of his production to the grid. The maximum savings are guaranteed by the cooperation of the two agents in such a way that one of them allows the other to maximize its own earnings. In a cooperative view, the gain is shared between the agents. In this context, it is observed that one agent oversizes his plant, while the second one builds a PV similar to the scenarios 1 and 2.

- In all four scenarios, although they have different supply-demand profiles, very similar total savings are achieved. This depends on the possible combinations that the agents manage to create. In some cases, making the most of mutual exchange, in other cases producing and exchanging with the network, so as to reduce costs. The best case, however, is the one characterized by excess supply and asymmetric and complementary load curves.

The novelty of our work can be summarized in two main points: (i) RO methodology is used to identify the optimal size of the PV plant, the quantity of P2P-traded and self-consumed energy; (ii) by studying the different characteristics of supply and demand, four scenarios can be identified. Comparison of the feasible mathematical solutions and the daily 24-hour load curves allow, for each scenario, to identify the optimal combinations to maximize savings.
The reminder of the paper is the following: in Section 2, we present the basic setup of our model. In Section 3, we determine the expected net energy cost to be borne by each prosumer once the PV project has been activated. In section 4 we set the optimization problem with the aim to identify the prosumers' optimal capacities of the PV system and describe our four EC exchange scenarios. For each of the latter, we find analytically the respective prosumers' optimal capacities in Appendix A.4. In section 5, we present model calibration. Section 6 shows our main results and discussion. Section 8 concludes.

2 The basic setup

Consider two agents ($i = 1, 2$) who currently purchase energy from a national provider (N, hereafter) at a constant unit energy price $p > 0$.
The two agents contemplates the opportunity of setting up an EC, where they would act as *prosumers*. In order to do so, they must cooperatively invest in a project for the installation of i) two individual PV systems and ii) a SG, allowing them to exchange energy with each other, i.e. energy community exchange, and with N.
To set up our model, we introduce the following assumptions: [14]

[14]Note that, in terms of model set-up, we share some of our assumptions with Castellini et al. (2020), such as our assumptions 7, 8, 9.

Assumption 1 ***(project time horizon)****. The investment project, once undertaken, lasts forever.*

Assumption 2 ***(individual energy demand).*** *The energy demand of each prosumer i is constant overtime, normalized to 1 and it is covered as follows:* [15]*:*

$$1 = \xi_i \cdot \alpha_i + \gamma_i + b_i \qquad \text{with } i = 1, 2, \tag{1}$$

where

- α_i represents the power capacity of the PV system installed by each prosumer i. Note that, at no loss for what may concern our results, we assume that the PV system, once installed, delivers at each generic time period t an amount of energy equal to the power capacity.
- $\xi_i \in [0, 1]$ is the proportion of α_i destined to self-consumption.[16]
- γ_i is the amount of energy that each prosumer i purchases from the other prosumer j, with $i, j = \{1, 2\}$ and $i \neq j$.
- $b_i \geq \bar{b} > 0$ is the amount of energy that prosumer i purchases from N, where $\bar{b} > 0$ is the night-time individual energy demand that must necessarily be covered by purchasing energy from N.[17]

Hence, summing up, the individual energy demand at each time period t can be covered as follows:

$$\begin{aligned} 1 = &\text{ Energy produced and self-consumed, i.e. } \xi_i \cdot \alpha_i \\ &+ \text{ Energy purchased from the other prosumer, i.e. } \gamma_i \\ &+ \text{ Energy purchased fromt the national grid, i.e. } b_i, \quad \text{with } i = 1, 2. \end{aligned}$$

Assumption 3 ***(energy prices).*** *On the energy market, the prosumers can: i) purchase energy only from N at a constant price $p > 0$ and ii) sell the energy produced by their own PV systems only to N at price q_t.*[18] *We assume that*

[15]Considering the day (i.e., 24 h) as time reference, equation 1 may be rewritten as follows:

$$\xi_i \cdot \alpha_i + \gamma_i + b_i \; = 1 = \int_0^{24} l(s)\, ds \tag{1.1}$$

where $l(s)$ denotes the instantaneous consumption of energy at each time $s \in [0, 24]$.

[16]The prosumer's instantaneous self-consumption depends on i) the load profile, ii) the location and iii) the renewable energy technology applied and it is, in general, represented as a weakly concave function of the power capacity α_i, i.e. $\xi_i(0)$, $\xi_i'(\alpha_i) > 0$ and $\xi_i''(\alpha_i) \leq 0$. However, based on scientific evidence by, among others, Bellekom et al. (2016), Velik and Nicolay (2016),Pillai et al. (2014) and Mondol et al. (2009), the assumption of a linear function is not too restrictive and provides a reasonable representation of the reality.

[17]The amount of energy $\bar{b}$ corresponds to the time interval in which the PV plant is not operating. Note that, in general, its magnitude may depend on the prosumer's daily load patterns, and may be lowered by installing a PV systemLuthander et al. (2015).

[18]Note that we are implicitly assuming that the prosumers are price-taker. This is justified by the focus set on investment decisions taken by agents who, due to the small size of their PV plants, are not able to influence the market's price.

the selling price q_t is stochastic and evolves overtime according to the following Geometric Brownian Motion (GBM):[19]

$$dq_t/q_t = \theta dt + \sigma d\omega_t, \quad with\ q_0 = q. \tag{2}$$

where θ is the drift rate, σ is the volatility rate, and $d\omega_t$ is the increment of the standard Wiener's process satisfying $\mathbb{E}[d\omega_t] = 0$ and $\mathbb{E}\left[d\omega_t^2\right] = dt$.
Process (2) implies that at a generic $t \geq 0$, the price level q_t is log-normally distributed with mean equal to $\ln q + (\theta - \frac{\sigma^2}{2})t$ and variance equal to $\sigma^2 t$. Furthermore, note that as process (2) is memoryless (i.e. Markovian), the observed q_t is the best predictor of future prices available at time t.

Assumption 4 ***(information on prices).*** *The prosumers receive information about buying and selling market prices at the beginning of each time period t. For the sake of simplicity, we assume that they can only trade energy on the energy market at this specific time point.*

By Assumption 4, once informed about buying and selling prices, the prosumers decide whether they should sell i) the entire amount of energy produced by their own PV system to N or ii) only part of it, keeping the residual for self-consumption or for the EC exchange.

Assumption 5 ***(EC exchange price).*** *The prosumers agree to exchange energy at the price v_t, which is defined as follows:*

$$v_t = mp + (1-m)q_t \qquad with \quad 0 < m < 1, \tag{3}$$

where, as showed in Appendix A.1, by m and $1-m$, with $m \in (0,1)$, we denote the seller's and buyer's strength exerted in the price bargaining.[20] Note that, when the buying price,p, is higher than the selling price q_t the EC exchange is always more convenient than purchasing from/selling energy to N since $v_t < p$ and $q_t < v_t$, respectively.

[19]The GBM is largely used in the field of Real Options and renewable energy (see review of the literature provided by Kozlova (2017)). However, it is important to underline the discussion provided by Borovkova and Schmeck (2017). In their work, they state that a Brownian motion alone, neither in an arithmetic nor geometric form, would be appropriate as the basis model, since electricity prices exhibit more complex features than stock prices. On the other hand, Andreis et al. (2020) provide a complete discussion on the approximation of electricity spot prices with a GBM, clarifying that, even though this process does not provide a realistic representation of the electricity price dynamics, it represents one of the best solution to derive explicit pricing formulae for call options, allowing to present in the most clear way the main features of the model. Since the aim of our work requires closed form solutions to investigate in depth the research question, we acknowledge the discussion on the GBM process and stick to the perspective provided by Andreis et al. (2020).

[20]Zafar et al. (2018) state that the energy price's negotiation is a challenging part of the SG set-up. The model presented by Alam et al. (2013) sets the energy price of the micro-grid in a specific time slot to vary from 0 to the grid energy price. Mengelkamp et al. (2017) design the P2P market such that prosumers and consumers trade with each other individually and in a randomized order on a pay-as bid basis and local prices (thus prices within the micro-grid) are expected to converge to grid prices under perfect information.

Assumption 6 ***(the investment cost function).*** *Prosumers take the investment decision cooperatively, meaning that at a certain point in time they decide jointly to undertake the investment, paying a sunk cost $I(\alpha_1, \alpha_2)$ for the PV plant set up and securing a total expected production equal to $\alpha_1 + \alpha_2$. The investment cost function is:* [21]

$$I(\alpha_1, \alpha_2) = K_A + K_B \cdot \sum_{i=1}^{2} \frac{\alpha_i^2}{2} \tag{4}$$

where $K_A > 0$ represents the cost to be undertaken in order to install the SG and $K_B > 0$ is a dimensional cost parameter associated with the installation of each individual PV system.
Note that, as for the set-up of the PV system, the investment cost is increasing and convex in the amount of energy produced by each prosumer, i.e. α_i. Differently, the cost associated with the installation of the SG is not affected by the amounts of energy produced by the two prosumers.[22]

Assumption 7 ***(the cost of solar energy).*** *The unit cost of producing solar energy is nil.*[23]

Assumption 8 ***(the discount rate).*** *The two prosumers are risk neutral agents and maximize the expected net present value of the PV investment project. Both discount future payoffs using the interest rate r, where $r > \theta$.* [24]

Assumption 9 ***(no storability)****. The energy produced by the PV plant at each time period t cannot be stored.*

Storability would be highly beneficial for the two prosumers as it would provide additional flexibility in the destination of the energy produced. By Assumption (9), we exclude the possibility of storing energy since, in spite of some promising progresses, storage technologies are still far from being cost effective.[25]

[21]We consider a quadratic function for the sake of simplicity. None of our results would be affected if a more general formulation, such as $I(\alpha_1, \alpha_2) = K_A + K_B \cdot \sum_{i=1}^{2} \frac{\alpha_i^\delta}{\delta}$ with $\delta > 1$ is assumed.

[22]As the number of EC members increase, each individual member may benefit from economies of scale for what concerns the fixed cost component K_A.

[23]Since solar radiations represent the production input and are for free, the marginal production costs for the PV power plants may considered negligible (Bertolini et al., 2018, Tveten et al., 2013, Mercure and Salas, 2012).

[24]Convergence of the model requires the trend in the price evolution not to exceed the discount rate. Last, note that in order to use an interest rate incorporating a proper risk adjustment, expectations should be taken with respect to a distribution of q_t adjusted for risk neutrality. See Cox and Ross (1976) for further details.

[25]See De Sisternes et al. (2016), ESG (2016) and ESG (2016)

3 The expected energy cost after the activation of the PV project

In this Section, we determine the expected energy cost to be borne by each prosumer once the PV project has been activated. Before proceeding, the following set of feasibility constraints is needed in order to fully characterize the EC exchange:

i) Each prosumer cannot purchase from the other prosumer more than the amount that the other prosumer does not self-consume, that is:

$$\gamma_i \leq (1-\xi_j) \cdot \alpha_j, \quad \text{with } i,j = \{1,2\} \text{ and } i \neq j. \tag{5}$$

ii) Each prosumer does not purchase from the other prosumer more that s/he actually needs,that is:[26]

$$0 < \gamma_i \leq (1-\bar{b}) - \xi_i \cdot \alpha_i, \quad \text{with } i,j = \{1,2\} \text{ and } i \neq j. \tag{6}$$

Let's denote by c_i the net energy cost of prosumer i at the generic time period t. The following two scenarios must be considered:

1. *No self-consumption and mutual exchange (NSCE):*

$$c_i^{NSCE}(q_t;\alpha_i) = p - \alpha_i q_t, \quad \text{for } i = \{1,2\}; \tag{7}$$

2. *Self-consumption and mutual exchange (SCE):*

$$\begin{aligned} c_i^{SCE}(q_t;\alpha_i,\gamma_i,\gamma_j) &= (1-\xi_i\alpha_i-\gamma_i)\,p + (\gamma_i-\gamma_j)[mp+(1-m)q_t] + \\ &\quad -(\alpha_i-\xi_i\alpha_i-\gamma_j)\,q_t \\ &= p - \alpha_i q_t + S_i(q_t;\alpha_i,\gamma_i,\gamma_j)(q_t-p), \qquad (8) \\ \text{for} &\quad i,j=\{1,2\} \text{ with } i\neq j. \\ \text{where} &\quad S_i(q_t;\alpha_i,\gamma_i,\gamma_j) = \xi_i\alpha_i + (1-m)\gamma_i + m\gamma_j. \qquad (9) \end{aligned}$$

Note that, as for the amount of energy produced by her/his own PV system, each prosumer chooses how much energy should be sold to N rather than be self-consumed or sold to the other prosumer. Hence, at each time period t, the prosumer energy cost, c_i, can be minimized by solving the following problem:[27]

$$\begin{aligned} c_i(q_t;\alpha_i,\alpha_j,\gamma_i,\gamma_j) &= \min[c_i^{NSCE}(q_t;\alpha_i), c_i^{SCE}(q_t;\alpha_i,\gamma_i,\gamma_j)] \\ &= p-\alpha_i q_t + \min\{0, S_i(q_t;\alpha_i,\gamma_i,\gamma_j)(q_t-p)\}. \qquad (10) \end{aligned}$$

[26] When $q_t < p$, $b_i = \bar{b}$ since purchasing energy from the other prosumer at price v_t is cheaper than purchasing it from N at price p.

[27] Note that in the following we omit for notational convenience that all the equations holds for $i,j=\{1,2\}$ with $i \neq j$.

The solution of Problem (10) is:

$$c_i\left(q_t;\alpha_i,\alpha_j,\gamma_i,\gamma_j\right)=\begin{cases}c_i^{NSCE}\left(q_t;\alpha_i\right), & \text{for } q_t>p,\\ c_i^{SCE}\left(q_t;\alpha_i,\gamma_i,\gamma_j\right), & \text{for } q_t\leq p,\end{cases} \tag{11}$$

since:

$$\begin{aligned}c_i^{NSCE}\left(q_t;\alpha_i\right)<c_i^{SCE}\left(q_t;\alpha_i,\gamma_i,\gamma_j\right) \quad \text{for} \quad q_t>p\\ c_i^{NSCE}\left(q_t;\alpha_i\right)\geq c_i^{SCE}\left(q_t;\alpha_i,\gamma_i,\gamma_j\right) \quad \text{for} \quad q_t\leq p\end{aligned}$$

Let's now firstly consider the range of values $q_t>p$ and denote by $C_i^{NSCE}\left(q_t;\alpha_i\right)$ the expected present value taken at the generic time period $t\geq 0$ of the flow of periodic net energy costs to be paid over the assumed time horizon. Using standard arguments, $C_i^{NSCE}\left(q;\alpha_i\right)$ solves the following Bellman equation:

$$C_i^{NSCE}\left(q_t;\alpha_i\right)=c_i^{NSCE}\left(q_t;\alpha_i\right)dt+\mathbb{E}_t\left[e^{-rdt}C_i^{NSCE}\left(q_{t+dt};\alpha_i\right)\right], \tag{12}$$

where the first term is the net energy cost borne over the generic time interval $(t,t+dt)$ and the second term is the continuation value.
By a straightforward application of the Ito's Lemma to Eq. (12), $C_i^{NSCE}\left(q;\alpha_i\right)$ can be determined by solving the following differential equation:

$$\Gamma C_i^{NSCE}\left(q_t;\alpha_i\right)=-c_i^{NSCE}\left(q_t;\alpha_i\right), \quad \text{for } q_t>p, \tag{11.1}$$

where $\Gamma=-r+\theta q\frac{\partial}{\partial q_t}+\frac{1}{2}\sigma^2q_t^2\frac{\partial^2}{\partial q_t^2}$ is a differential operator.
Let's now turn to the range of values $q_t<p$ and denote by $C_i^{SCE}\left(q_t;\alpha_i,\gamma_i,\gamma_j\right)$, the expected present value taken at the generic time period $t\geq 0$ of the flow of periodic net energy costs to be paid over the assumed time horizon. As above, $C_i^{NSCE}\left(q;\alpha_i\right)$ is the solution of the following Bellman equation:

$$\begin{aligned}C_i^{SCE}\left(q;\alpha_i,\alpha_j,\xi_i,\gamma_i,\gamma_j\right) \quad = \quad & c_i^{SCE}\left(q_t;\alpha_i,\gamma_i,\gamma_j\right)dt\\ & +\mathbb{E}_t\left[e^{-rdt}C_i^{SCE}\left(q_{t+dt};\alpha_i,\gamma_i,\gamma_j\right)\right]\end{aligned} \tag{13}$$

where the first term is the net energy cost borne over the generic time interval $(t,t+dt)$ and the second term is the continuation value.
By applying the Ito's Lemma to Eq. (12), $C_i^{NSCE}\left(q;\alpha_i\right)$ can be determined by solving the following differential equation:

$$\Gamma C_i^{SCE}\left(q_;\alpha_i,\gamma_i,\gamma_j\right)=-c_i^{SCE}\left(q_t;\alpha_i,\gamma_i,\gamma_j\right), \text{for } q_t<p \tag{12.1}$$

The solutions of Eqs. (11.1) and (12.1) are subject to the following boundary Conditions:

$$\lim_{q_t\to\infty}C_i^{NSCE}\left(q_t;\alpha_i\right)=\frac{p}{r}-\alpha_i\frac{q_t}{r-\theta}, \tag{11.2}$$

and

$$\lim_{q_t\to 0}C_i^{SCE}\left(q_t;\alpha_i,\gamma_i,\gamma_j\right)=\frac{p}{r}-\alpha_i\frac{q_t}{r-\theta}-S_i\left(q_t;\alpha_i,\gamma_i,\gamma_j\right)\left(\frac{p}{r}-\frac{q_t}{r-\theta}\right) \tag{12.2}$$

respectively. The term $\frac{p}{r} - \alpha_i \frac{q_t}{r-\theta}$ represents the expected present value of the flow of the net energy costs conditional on i) purchasing all the energy needed by prosumer i from N and ii) selling all the energy produced by his/her the PV system to N. This is, of course, the case when $q_t > p$. Further, note that, if the capacity installed is sufficiently high, i.e. $\alpha_i > \frac{p}{r} / \frac{q_t}{r-\theta}$, the prosumer earns a profit. In contrast, when $q_t < p$, self-consumption and mutual exchange of energy are more convenient than trading energy (selling to and buying from) with N. The expected present value of the flow of periodic gains associated with self-consumption and mutual exchange of energy is equal to $S_i\left(q_t; \alpha_i, \gamma_i, \gamma_j\right)\left(\frac{p}{r} - \frac{q_t}{r-\theta}\right)$ which is, consistently, decreasing in q_t.
As shown in Appendix A.2, by the linearity of Eq. (11.1)and (12.1) and taking into account Condition (11.2) and (12.2), the solution of the prosumer's cost minimization problem, i.e.

$$\begin{array}{ll} \Gamma C_i^{NSCE}\left(q_t; \alpha_i\right) = -c_i^{NSCE}\left(q_t; \alpha_i\right), & \text{for } q_t > p, \\ \Gamma C_i^{SCE}\left(q_t; \alpha_i, \gamma_i, \gamma_j\right) = -c_i^{SCE}\left(q_t; \alpha_i, \gamma_i, \gamma_j\right), & \text{for } q_t < p, \end{array} \tag{14}$$

is:

$$C_i\left(q_t; \alpha_i, \gamma_i, \gamma_j\right) = \begin{cases} C_i^{NSCE}\left(q_t; \alpha_i\right) = \frac{p}{r} - \alpha_i \frac{q_t}{r-\theta} \\ \qquad + S_i\left(q_t; \alpha_i, \gamma_i, \gamma_j\right) X^{NSCE}\left(\frac{q_t}{p}\right)^{\beta_2} \\ \qquad\qquad \text{for} \quad q_t > p, \\ C_i^{SCE}\left(q_t; \alpha_i, \gamma_i, \gamma_j\right) = \frac{p}{r} - \alpha_i \frac{q_t}{r-\theta} \\ \qquad - S_i\left(q_t; \alpha_i, \gamma_i, \gamma_j\right)\left[\left(\frac{p}{r} - \frac{q_t}{r-\theta}\right) - Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right] \\ \qquad\qquad \text{for} \quad q_t < p, \end{cases} \tag{15}$$

where $\beta_2 < 0$ and $\beta_1 > 1$ are the roots of the characteristic equation $\Phi(x) \equiv \frac{1}{2}\sigma^2 x(x-1) + \theta x - r$ and

$$X^{NSCE} = \frac{p}{r-\theta} \frac{r - \theta\beta_1}{r\left(\beta_2 - \beta_1\right)} \leq 0, \tag{16}$$

$$Y^{SCE} = \frac{p}{r-\theta} \frac{r - \theta\beta_2}{r\left(\beta_2 - \beta_1\right)} \leq 0. \tag{17}$$

In the first branch of $C_i\left(q_t; \alpha_i, \gamma_i, \gamma_j\right)$, the term $S_i\left(q_t; \alpha_i, \gamma_i, \gamma_j\right) X^{NSCE}\left(\frac{q_t}{p}\right)^{\beta_2}$ represents the expected present value of the option to switch from the $NSCE$ to the SCE scenario as soon as $q_t < p$. Note that the closer q_t to p, the lower the stochastic discount factor $\left(\frac{q_t}{p}\right)^{\beta_2}$ and, consequently, the higher the value of the option to switch. This is because the expected amount of time that the prosumer must wait before switching is lower.
Turning to the second branch of $C_i\left(q_t; \alpha_i, \gamma_i, \gamma_j\right)$, the term $S_i\left(q_t; \alpha_i, \gamma_i, \gamma_j\right) Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}$ represents the value associated with the option to switch from the SCE to the

$NSCE$ scenario as soon as $q_t > p$. As above but moving from below this time, the closer $q_t$to p, the lower the stochastic discount factor $\left(\frac{q_t}{p}\right)^{\beta_1}$ and the higher the value of the option to switch. This is because the switch will occur earlier in expected terms.

4 The optimal PV system's capacities

In this Section, we determine the optimal PV system's capacities that each prosumer should install in order to maximize the value of the joint investment project. Let's start by identifying the project's value considering, for the sake of simplicity, a scenario where self-consumption and EC exchange would be, once the investment is activated, immediately convenient, i.e. when $q_t < p$.
A necessary condition for investing in the project is benefiting from it with respect the status quo scenario, that is, not producing on her/his own energy and covering own needs by purchasing energy from N at price p. In Appendix A.3, we show that this condition is met since:

$$\Delta C_i\left(q_t; \alpha_i, \gamma_i, \gamma_j\right) = \frac{p}{r} - C_i\left(q_t; \alpha_i, \gamma_i, \gamma_j\right) > 0, \tag{18}$$

that is, the energy cost associated with the status quo scenario, i.e. $\frac{p}{r}$, which, once invested, is implicitly saved, and it is higher than the expected energy cost associated with the PV project, i.e. $C_i\left(q_t; \alpha_i, \gamma_i, \gamma_j\right)$.
By Assumption (6), the two prosumers take the investment decision cooperatively, which implies that they determine jointly the optimal capacities of their PV systems. The optimal pair, (α_1^*, α_2^*) must be such that the expected net present value of the PV project is maximized. Formally:

$$\begin{aligned} \left(\alpha_1^*, \alpha_2^*\right) &= \arg\max \mathcal{O}\left(\alpha_1, \alpha_2\right), \\ & \quad \text{s.t.} \quad (5) \quad \text{and} \quad (6) \quad \text{hold} \end{aligned} \tag{19}$$

and where

$$\begin{aligned} O\left(\alpha_1, \alpha_2\right) &= \Delta C_1\left(q_t; \alpha_1, \gamma_1, \gamma_2\right) + \Delta C_2\left(q_t; \alpha_2, \gamma_2, \gamma_1\right) - I(\alpha_1, \alpha_2) \\ &= \left(\xi_1 \alpha_1 + \gamma_1 + \xi_2 \alpha_2 + \gamma_2\right)\left[\frac{p}{r} - \frac{q_t}{r-\theta} - Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right] + \\ & \quad + \left(\alpha_1 + \alpha_2\right)\frac{q_t}{r-\theta} - I\left(\alpha_1, \alpha_2\right) \end{aligned} \tag{20}$$

is the expected net present value of the PV project.
We now investigate the investment decision under four different *EC exchange scenarios*. Each of them is characterized by different constraints in terms of energy exchanged P2P, leading to specific feasibility conditions. Next, we present the overall framework for each scenario, while in Appendix A.4 we show the respective feasible mathematical solutions of Problem (19), distinguishing the internal solutions and the corner solutions. However, it must be stressed that

the mathematical solutions are not always feasible in a real context, as they may identify daily supply and demand pairings that cannot be realized over a 24-hour period for two representative agents. In Section 6 we provide discussion on the real feasibility of the scenarios according to the outcomes obtained from the calibration of the model and in line with the mathematical results found in Appendix A.4.

Scenario 1: excess supply in the EC energy exchange. In Scenario 1 we focus on the case of excess of supply from both prosumers in exchange P2P and the constraint presented in Eq. (6) is detailed as follows[28]:

$$0 < (1 - \bar{b}) - \xi_1\alpha_1 < (1 - \xi_2)\alpha_2, \tag{21}$$

$$0 < (1 - \bar{b}) - \xi_2\alpha_2 < (1 - \xi_1)\alpha_1 \tag{22}$$

In the mid of both Inequalities (21) and (22), we find the quantity of energy that each prosumer demand to the other prosumer, i.e. $(1 - \bar{b}) - \xi_1\alpha_1$ and $(1-\bar{b})-\xi_2\alpha_2$, that is, the residual quantity of energy needed once i) purchased the amount $\bar{b}$ from N [29] and ii) consumed his/her own produced energy, i.e. $\xi_1\alpha_1$ and $\xi_2\alpha_2$. Both amounts must, of course, be positive. On the RHS we find instead the quantity of energy that the other prosumer could actually supply, that is, the residual quantity of energy produced not self-consumed, i.e. $(1 - \xi_2)\alpha_2$ and $(1-\xi_1)\alpha_1$. As it can be immediately seen, under this scenario, the EC exchange is characterized by an excess supply since $(1-\bar{b})-\xi_i\alpha_i] < (1-\xi_j)\alpha_j$ for $i, j = 1, 2$ with $i \neq j$. In other words, the quantity of energy demanded by each prosumer is lower than the quantity that the other prosumer could actually provide.

Scenario 2: excess demand in the EC energy exchange In Scenario 2 there is excess of demand from both prosumers and Eq. (6) becomes:

$$(1 - \bar{b}) - \xi_1\alpha_1 \geq (1 - \xi_2)\alpha_2 > 0, \tag{23}$$

$$(1 - \bar{b}) - \xi_2\alpha_2 \geq (1 - \xi_1)\alpha_1 > 0. \tag{24}$$

If Inequalities (23 and/or (24) hold strictly, the quantity of energy that each prosumer demand to the other prosumer, i.e. $(1 - \bar{b}) - \xi_i\alpha_i$, is higher than the quantity of energy that each prosumer may actually supply, i.e. $(1 - \xi_j)\alpha_j$. This implies that the EC exchange is characterized by an excess demand since $(1-\bar{b})-\xi_i\alpha_i] > (1-\xi_j)\alpha_j$ for $i, j = 1, 2$ and $i \neq j$. Otherwise, if (23 and/or (24) hold with the equality, the quantity of energy demanded equals the quantity of energy supplied.

[28] Eq. (21) refers to prosumer 1 and (22) to prosumer 2. The same occurs in the following scenarios.

[29] We remind that when $q_t < p$, $b_i = \bar{b}$ since purchasing energy from the other prosumer at price v_t is cheaper than purchasing it from N at price p.

Scenario 3: non complementarity in the EC exchange. Under Scenario 3, prosumer 1 demand less energy than the quantity that prosumer 2 could provide while prosumer 2 may need i) more energy than the quantity that prosumer 1 could provide or ii) exactly the quantity that prosumer 1 could provide. The constraint characterizing this scenario are the following:

$$0 < (1 - \bar{b}) - \xi_1 \alpha_1 < (1 - \xi_2)\alpha_2, \tag{25}$$

$$(1 - \bar{b}) - \xi_2 \alpha_2 \geq (1 - \xi_1)\alpha_1 > 0. \tag{26}$$

Scenario 4: non complementarity in the EC exchange. Scenario 4 is symmetric to scenario 3. In fact, in this case, prosumer 2 demand less energy than the amount that prosumer 1 could provide while prosumer 1 may need i) more energy than the quantity that prosumer 2 could provide or ii) exactly the quantity that prosumer 2 could provide.

$$(1 - \bar{b}) - \xi_1 \alpha_1 \geq (1 - \xi_2)\alpha_2 > 0, \tag{27}$$

$$0 < (1 - \bar{b}) - \xi_2 \alpha_2 < (1 - \xi_1)\alpha_1. \tag{28}$$

5 Calibration of the model

Concerning the unit price q_t paid to the prosumers selling energy to N, the dataset is built using hourly Italian Zonal Prices for Northern Italy from 2012 to 2018. The dataset[30] is built using Italian Zonal Prices, where q_t refers to Northern Italy region and time interval is set from 2012 to 2018. We take into account only the prices relative to the hours where the PV plant is operating, that is, from 8 a.m. to 7 p.m.. Average quarterly prices are then computed and seasonally adjusted.
To test whether the price q_t follows a GBM with drift, non stationarity is checked using the *Shapiro Test* [31] and the *Augmented Dickey-Fuller Test* (ADF) [32].
The drift rate, θ, and the volatility rate, σ, of the process for the price q_t are computed using the method of moments. Their estimates (θ, σ) are obtained by plugging the sample mean $(\hat{\theta})$ and variance $(\hat{\sigma})$ into $\theta = \left(\hat{\theta} + \frac{1}{2}\hat{\sigma}^2\right) dt$ and $\sigma = \frac{\hat{\sigma}}{\sqrt{dt}}$. The annual drift θ and the volatility σ are equal to 0.01 and 0.32, respectively.[33]

[30] The Italian power market is managed by the nationally owned transmission system operator (TSO) - *Gestore Mercati Energetici* (GME). Through its platform, producers and purchasers sell and buy wholesale electricity. Data are sourced from the GME website; *Source:* `https://www.mercatoelettrico.org/en/download/DatiStorici.aspx`.

[31] Shapiro-Wilk normality test: W = 0.94926, p-value = 0.2057

[32] Dickey-Fuller =-1.8958, Lag order = 3, p-value = 0.6124, alternative hypothesis: stationary. ADF test null hypothesis is failed be to rejected, thus non stationarity assumption is confirmed.

[33] The estimates were computed on the basis of quarterly average prices and then put in annual terms.

The value of the price q_t for both prosumers in assumed to be the average value over the reference time interval and it is set equal to 58.86 euro/Mwh.
The price paid by the prosumers to buy energy from the national grid (p) is set equal to 154.00 euro/Mwh, that is the maximum value of the electricity price paid by household consumers in the European Market.[34] The discount rate r results from the average of the values used in Bertolini et al. (2018) and it is set equal to 0.05.
The model calibration is performed normalizing the demand of energy to 1Mwh/y. The dimensional investment cost parameter K_B of the investment cost function $I(\alpha_1, \alpha_2)$ is computed following Bertolini et al. (2018). The unit of measure of the PV plant's size α_i is kWh/year. It is always possible to obtain the average amount of energy produced by the PV plant over a certain time interval in kWh, i.e., in a year. Following Bertolini et al. (2018) (Appendix B), the plant energy output is the product of the size (kWp) and the local solar insolation that takes capacity factor into account (kWh/kWp/year). If the cost of the plant per kWp is known, it is also possible to trace, using LCOE, the cost of the plant as a function of the energy produced in a year, as in the following equation: $K_B = 2\frac{LCOE}{r}\left(1 - e^{-rT}\right)$. This allows to construct a cost function in terms of kWh/year instead of kWp.
The assumed average plant life time, T, is set equal to 25 years.[35] The levelized cost of energy (LCOE) for the PV technology is set equal to 80 euro/MWh.[36] The parameter K_A represents the cost the prosumers pay to be connected to the SG and we set it equal to $0.15K_B$.[37]
Table 1 summarizes all the parameters used for the model calibration

[34]Eurostat - Energy Statistics, Electricity prices for household consumers - bi-annual data (from 2007 onwards) [nrg_pc_204]. The data are in Euro currency, refer to an annual consumption between 2 500 and 5000 kWh (Band-DC, Medium), excluding taxes and levies.

[35]See Branker et al. (2011),Kästel and Gilroy-Scott (2015).

[36]Lazard (2020) ranges the LCOE (unsubsidized) values for Solar PV Rooftop Residential from 154 to 227 USD/MWh, for Solar PV Rooftop CI from 74 to 179 USD/MWh, and for Solar PV Community from 63 to 94 USD/MWh.

[37]With reference to Italy, we set parameter K_A on the basis of the fees of these two projects: "REGALGRID"(https://www.regalgrid.com/), where the average fee is 400 euro/year (Peloso, 2018) and "sonnenCommunity" (https://sonnengroup.com/sonnencommunity/), where the monthly fee is 20 euro/month.

Parameter	Description	Value	Source/Reference
θ	drift	0.01	Calibrated on Northern Italy zonal prices, TSO GME
σ	volatility	0.32	Calibrated on Northern Italy zonal prices, TSO GME
q	average level of the price q_t over time period	58.85	Northern Italy zonal prices, TSO GME
p	cost to buy energy from the national grid	154.00	Eurostat
$\bar{b}$	minimum amount of energy prosumers buy from the national grid	0.40	Luthander et al. (2015), Weniger et al. (2014)
T	PV plant lifetime (years)	25	Branker et al. (2011), Kästel and Gilroy-Scott (2015)
r	discount rate	0.05	Bertolini et al. (2018)
$LCOE$	levelized cost of electricity for PV plants euro	80.00	Lazard (2020)
K_A	cost to set up the SG	342.48	Own computation, Peloso (2018)
K_B	PV dimensional investment cost parameter	2283.18	Own computation, Bertolini et al. (2018)
β_1	Root	1.41	Own computation
β_2	Root	-0.67	Own computation

Table 1: Parameters

6 Results

In this Section, we present the main findings obtained running our model as calibrated in Section 5. For each scenario[38], our aims are as follows: i) to investigate the role of self-consumption as a driver for setting up an EC (ξ_1, ξ_2), ii) to determine the optimal capacity of the individual PV system, i.e. (α_1^*, α_2^*), and iii) to determine the expected net present value of the PV project, i.e. $(O(\alpha_1^*, \alpha_2^*))$.

The solutions of Problem (19) leads to several feasible outcomes. However, some of them, even if mathematically sound, are not realistic. This is, for instance, the case for outcomes such as the ones where both prosumers exchange all the energy individually produced, i.e. no self-consumption, or they self-consume all the energy individually produced, i.e. no energy exchange (see appendix A.5). Another case is the situation in which the division of the day into production and hourly consumption does not allow supply and demand to meet in the same time slot, even if this equilibrium is mathematically contemplated in model like

[38]Note that we provide only the findings relative to Scenarios 1, 2 and 3. We do not consider Scenario 4 since findings would be symmetric with respect to those obtained in Scenario 3.

ours, where an entire day is compressed in an unique time point. Once again, this implies that, although some solutions are mathematically feasible, they identify supply and demand pairs that cannot occur over the course of a day, since they would ideally imply an instantaneous exchange of all quantities consumed during the day.
In the light of these remarks, in Table 2, we show the outcomes that, in our view, are the most representative of our four scenarios. Our selection takes into account the following requirements: 1. the outcomes are all mathematically feasible, as we show in the Appendix A.4; 2. we identify those outcomes that are consistent with realistic daily supply and demand curves; 3. we show the outcomes with the highest NPV. Interestingly, the outcomes we show have similar NPVs despite presenting very different supply and demand functions. Furthermore, we discuss the circumstances under which an EC may be set up and the roles played in this process by both prosumers and the national provider.
Computational details concerning each considered scenario are presented in Appendix A.5.

Parameters	*Scenario 1*	*Scenario 2*	*Scenario 3*
$\xi_1 \in$	$[0.43; 0.58]$	$(0.50; 1]$	$[0.51; 0.52]$
$\xi_2 \in$	$[0.43; 0.58]$	$(0.50; 1]$	$[0; 0.02]$
α_1^*	0.710	0.600	1.152
α_2^*	0.710	0.600	0.720
$\xi_1 \alpha_1^*$	0.360	0.426	0.593
$\xi_2 \alpha_2^*$	0.360	0.426	0.007
γ_1^*	0.240	0.173	0.007
γ_2^*	0.240	0.173	0.559
$\mathcal{O}(\alpha_1^*, \alpha_2^*)$	3301	3098	3012

Table 2: *Results*

In the following, we show the representative outcomes of the different scenarios, studying their characteristics in order to understand which is the best scenario and which are the elements that make it better than the other cases.
According to the requirements we have listed above, in the second column of Table 2, we present the outcome from scenario 1 paying the highest NPV and in Figure 1 we show a realistic combination of supply and demand that can support it.

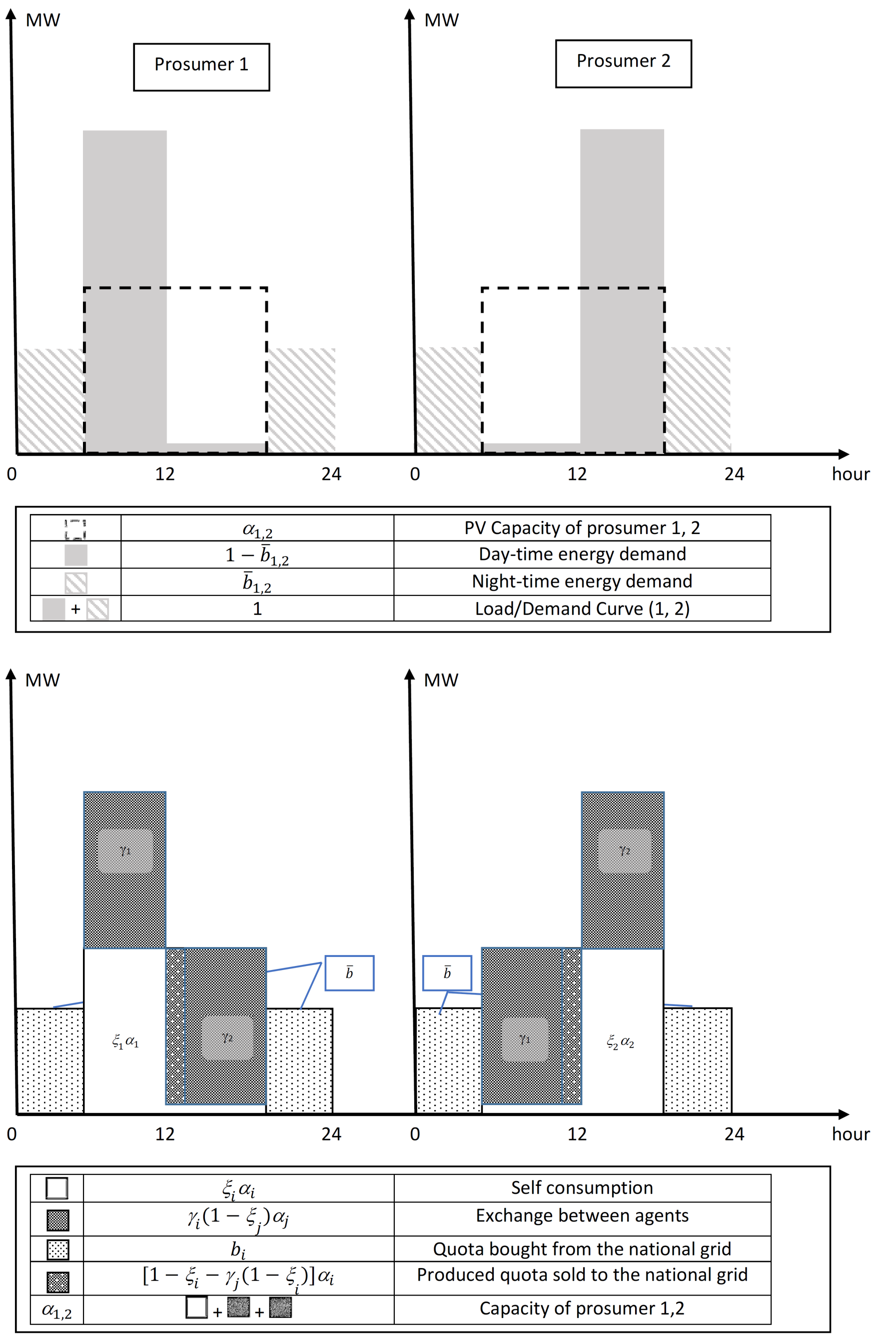

Figure 1: *Scenario 1* - Load and supply curves and distribution of energy trade and consumption.

In greater detail, at the top of Figure 1 we find, for each agent, the daily load curves over 24 hours and the amount of energy produced by each individual PV system. The dashed areas correspond to the night demand, while the grey areas correspond to the day demand. The dashed frame represents the capacity of the PV system. In the lower part of the diagram we show how the PV system's production is split between self-consumption, energy exchange with the other prosumer and sold to the national provider. In the similarly, we show how the individual demand is covered through self-consumption, energy exchange with the other prosumer and purchases from the national provider. The dark grey areas represent the energy exchange between the two agents, i.e. γ_1 and γ_2.
By Table 2, we can observe that the two prosumers have a production function of the same size (0.710) and asymmetric-complementary demand functions. In this way, one prosumer manages to sell its excess production to the other, exactly when the other agent needs it. The two prosumers, by acting cooperatively, thus manage to have an optimal symmetrical plant size (0.710) that allows avoiding the purchase of daytime energy from N. We remind that this scenario is characterized by excess supply. Therefore, the two prosumers are able to fully meet their own energy needs, without buying daytime energy from the national grid and, at the same time, each being able to sell 0.110 to the national grid. Self-consumption is about 50% of PV production, which corresponds to 36% of the total demand.
In the third column, we find the outcome from scenario 2. The NPV is very close to the one in scenario 3. We notice also that the two scenarios are very similar in terms of demand and supply composition. As can be seen, self-consumption is about 42,6% of the total demand, or about 71% of PV production. This scenario is characterized by excess demand from both prosumers. Among the feasible outcomes, the one having the highest NPV, is actually a corner solution in which the two agents manage to fully cover their demand with a mutual energy exchange. Again, the two demand functions are asymmetrical, as as shown by Figure 2.

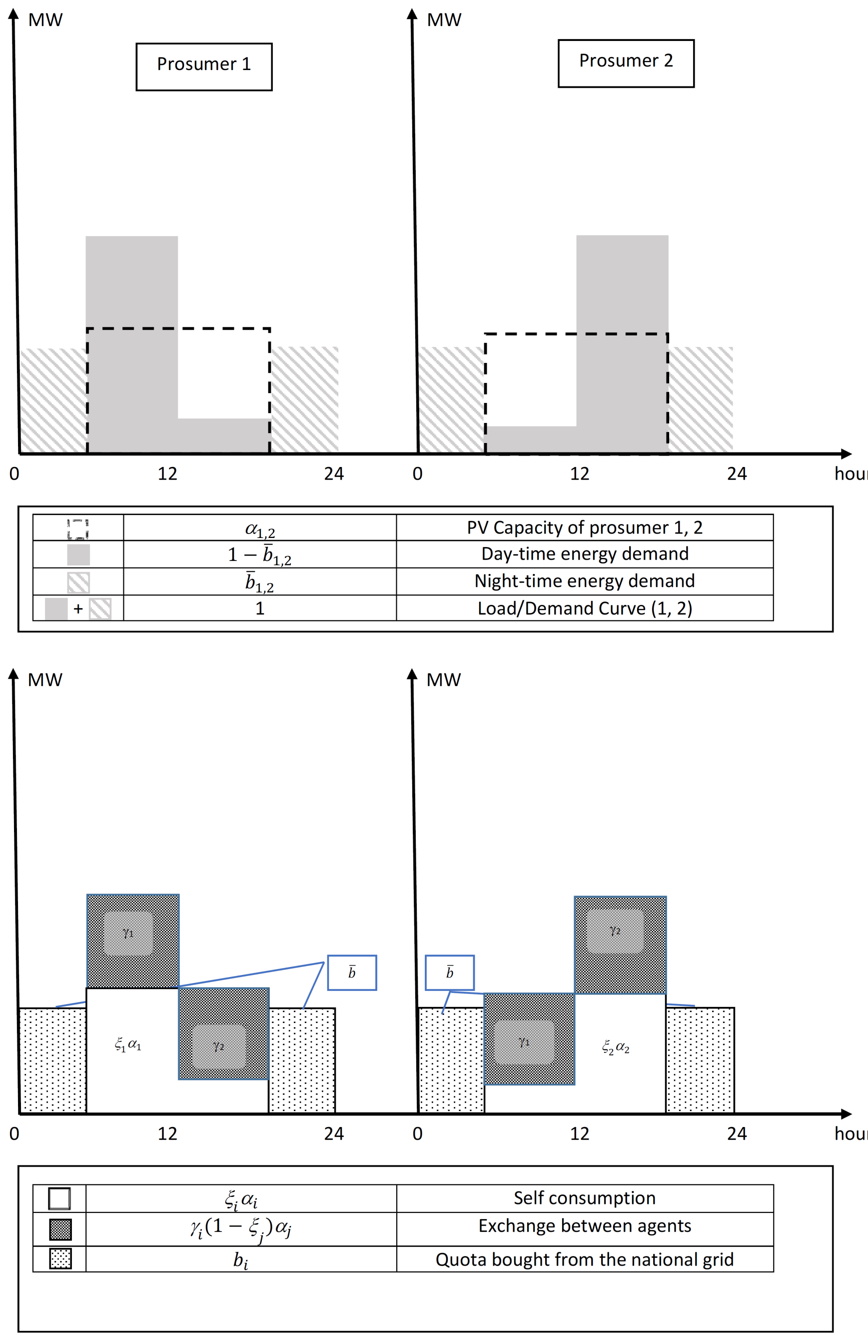

Figure 2: *Scenario 2, Corner Solution 3* - Load and supply curves and distribution of energy trade and consumption.

Compared to scenario 1, the two prosumers do not sell any energy to the national provider and we are in a situation in which the PV plant size is set at the maximum daytime consumption. In this way the two agents can minimize their costs, but they do not get an extra profit by selling excess of energy production to the national grid, as is the case in scenario 1. See for example, in the following figure 3, the results of the corner solution 1 of the scenario 2 (see the second column of the table 6 in the Appendix A.5). The two PV plant's sizes are equal to 0.535 and 0.488, while self-consumptions are 0.228 and 0.294, respectively. This case shows that although there is also an exchange of the produced energy of 0.194 and 0.306, the two prosumers cannot satisfy all the demand. They have to buy from the national grid an amount of 0.177, which is 18% of the total demand of one agent. This combination leads to a lower $\mathcal{O}\left(\alpha_1^*, \alpha_2^*\right)$ which is equal to 2823.

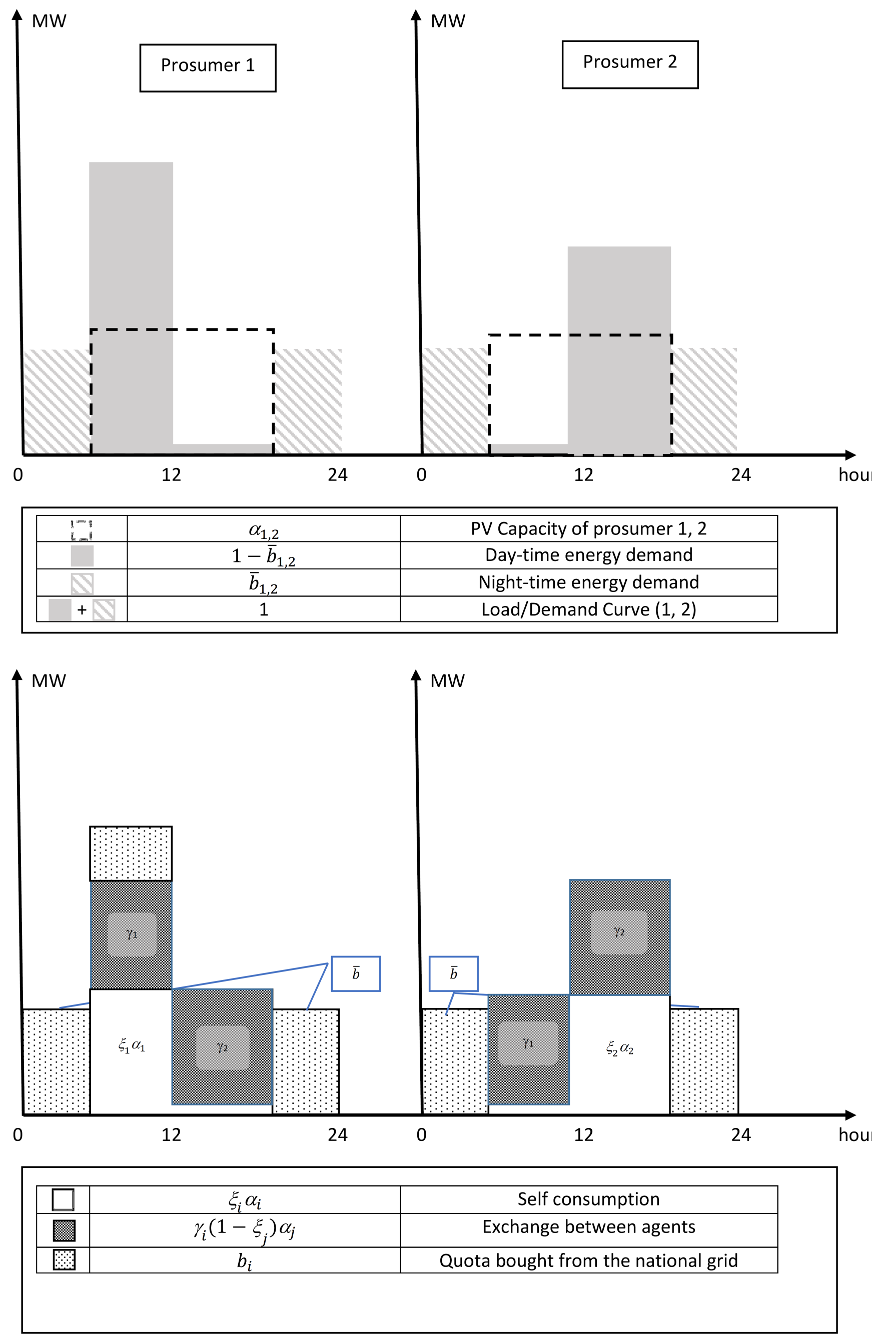

Figure 3: *Scenario 2* - Load and supply curves and distribution of energy trade and consumption.

About the scenario 2, we can conclude that the best outcomes are only feasible if the self-consumption levels (ξ_1 and ξ_2) are relatively high, in particular higher than 0.50. This requires a relatively small PV systems' capacity. Otherwise, the agents would have too much energy to be sold to the national provider and this would be sub-optimal. Indeed the PV plant's sizes are equal to 0.60. This allows, in proportion a high level of self-consumption, as the results show. The consideration of all these features justify a lower NPV.
Scenario 3 shows the non complementarity case; therefore our expectation is an asymmetric solution, because we are in a context where prosumer 1 needs in exchange not more than what the other prosumer could provide, while the prosumer 2 needs more than what the prosumer 1 could provide. The results in the last column of Table 2, show that agent 1 installs a PV capacity larger than its demand, i.e. 1.152, while prosumer 2, installs a PV plant of a size very similar to that obtained in scenario 1, i.e. 0.720. The interesting result is that, despite having a very different supply-demand structure, compared to the previous cases, the value levels generated are not very far from those obtained in scenario 2. In fact, we get an $\mathcal{O}(\alpha_1^*, \alpha_2^*)$ equal to 3012. Let's present the main insight behind this result.

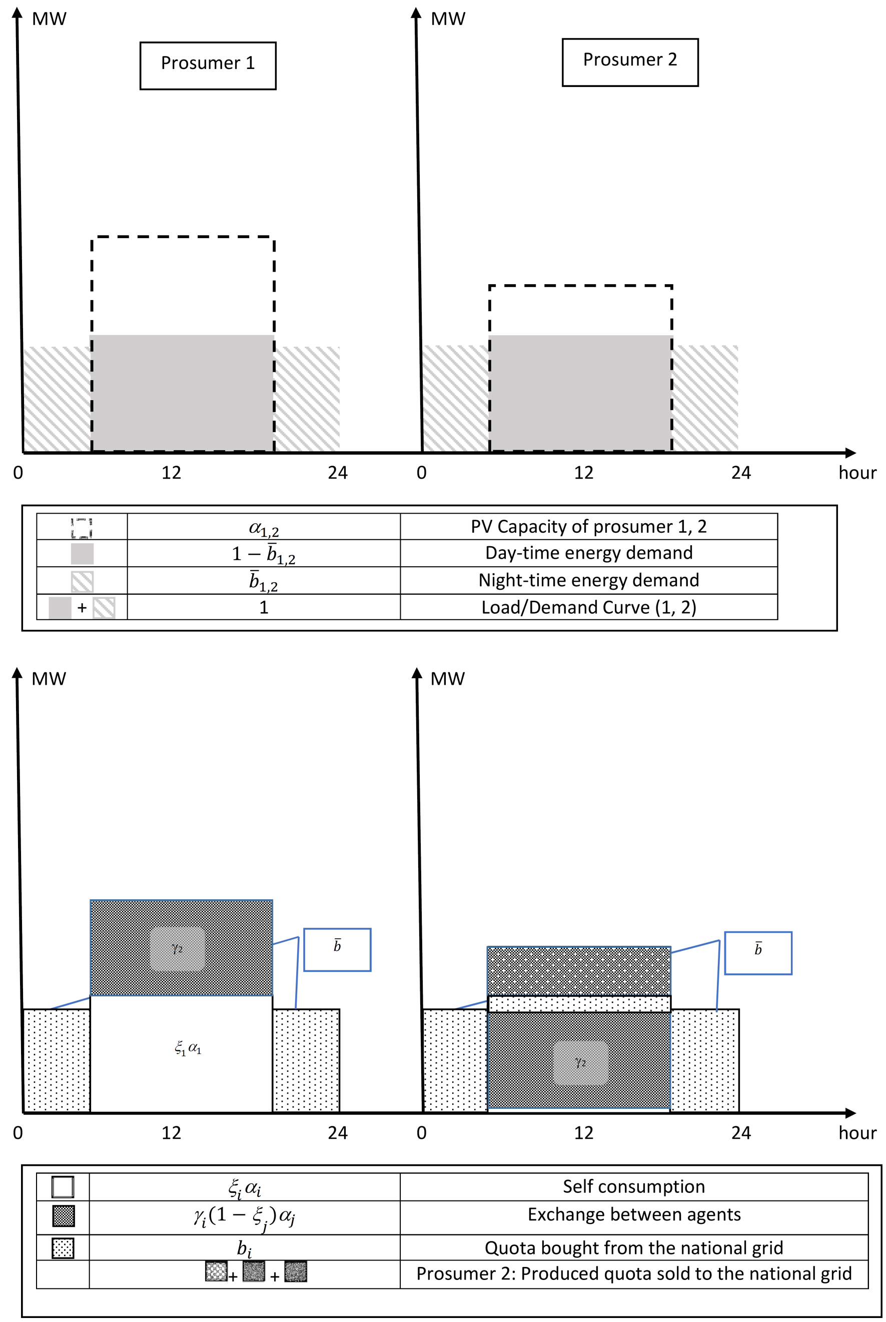

Figure 4: *Scenario 3* - Load and supply curves and distribution of energy trade and consumption.

The interesting result is that prosumer 1 self-consumes a little more than half of its production (0.593), while all the rest of the production is sold to the second agent (0.559). Prosumer 2, on the other hand, buys all the energy sold by agent 1 and sells almost all of its production to the grid, thus its self-consumption is almost nil. By doing so, the two prosumers manage to maximize their joint pay-offs, even though they are in a situation characterized by supply-demand asymmetry. Prosumer 2 sells to the national provider and purchases from prosumer 1 almost the same quantity of energy. For prosumer 2, this exchange is unprofitable compared to the self-consumption hypothesis, because his savings are lower. However, thanks to cooperation, the exchange is profitable in terms of overall total value for the agents. Prosumer 1 earns more than the lower savings of agent 2. The net effect is a NPV equal to 3012, very close to the other scenarios.
Although the result shows an NPV close to that of scenarios 1 and 2, this is still lower as the case where the two agents work in complement, which is still more advantageous. In this scenario, they exploit their own asymmetry by transforming an agent into a pure link between production and sale and playing on the difference in prices. All of this can only work with perfect coordination and cooperation between prosumers.
It is interesting at this point to consider whether it is worth building an EC with these characteristics. Let us now summarize our results by trying to reflect on the conditions that make convenient the set up of an EC. First of all, we have verified that not all the results that are mathematically feasible, and which we report in the related appendixes, make sense in reality. In fact, it is not always possible to find load curves satisfying the symmetry of the results with the asymmetry of the prosumers. We have shown that in scenario 1 (in scenario 2) an EC can exist only if the prosumers are almost perfectly asymmetrical and with self-consumption levels of about 40-50% of the PV production (70% for scenario 2) and the same day/night distribution. Therefore the EC only makes sense under certain conditions and with particular combinations of supply and demand. It could also be relevant in a context similar to scenario 3, where there is an asymmetrical structural situation and the two agents try to maximize the joint value of the PV project. Perfect cooperation between prosumers is crucial in this context.

7 Conclusions

In this work, we have modelled the investment decision of two prosumers in a PV system in a SG framework. Each prosumer can: (i) self-consume its energy production, (ii) exchange energy with the national grid, and/or (iii) exchange energy with the other agent. Uncertainty is taken into account by the dynamics of the price the prosumers receive for the energy sold to the national provider, which is assumed to be stochastic. We investigate the investment decision, irreversible and taken cooperatively, under different prosumers' behaviors, taking into account all the possible combinations of energy demand and supply for the

two prosumers. These are summarized in four different exchange scenarios.
Our findings show that not in all the cases it is convenient to develop an EC. Indeed, after having calibrated our model on the Northern Italy energy market, we have calculated the mathematical feasibility of our investment decisions model under the four different scenarios. Among all these outcomes only some are also realistic, because not always it is possible to find load curves satisfying the symmetry of the results with the asymmetry of the prosumers.
We have found the prosumers' supply and demand profiles for which it makes sense to build an EC. The best case is when the two prosumers have excess demand in P2P exchange, and characterized by perfectly asymmetric and complementary supply and load curves. In this case, the two prosumers build two symmetrical PV plants of a size smaller compared to their demand, where: a share of the energy production is self-consumed, a share is exchanged P2P with the aim to match the hourly consumption demand reciprocally and a share is sold to N. Nothing is bought in daytime consumption form N.
A second feasible scenario refers to the case where the two prosumers are characterized by excess demand. Both produce and consume with a smaller plant respect to the previous one and set at the daytime demand level. Nothing is sold and purchased to and from the national grid in the daytime. The EC is also convenient with asymmetry between the two agents. Indeed, if one prosumer has excess demand and the other has excess supply, our model find a positive NPV, when an agent produces to self-consume and sell, and a second one buys the surplus of the other and sells all of his production to N. The maximum savings are guaranteed by the cooperation in investment decisions of the two agents in such a way that one allows the other to maximize its own earnings. In a cooperative view, the gain is shared between the agents. In this context, one prosumer oversizes his PV plant, while the second one builds it with a size lower than his demand. Therefore the EC only makes sense under certain conditions and with particular combinations of supply and demand, although we found that the EC could have a closer NPV while showing different and opposite supply and demand profiles. Much depends on the degree of self-consumption, the size of the PV system and the level of cooperation between agents.
To conclude, since it is widely recognized that policymakers support the deployment of the EC due to their promising positive impact in terms of i) achievement of the decarbonization goals, ii) potential in the improvement in the electricity network's management, and iii) active involvement of the prosumers in the energy market, on the basis of our findings, it is important to remark that further research must be developed on the conditions assuring the optimal arising of the EC. Aspects like uncertainty, demand and supply matching in exchange P2P and PV plant optimal sizing must deepened with the aim to support policymakers in their future task to provide an "enabling regulatory framework for citizen energy communities" (EU (2019)). Lastly, possible extensions of our research could be focused on deepening: i) the main drivers of uncertainty in an EC framework, ii) the topic of different EC network's structures, in terms of existence conditions as well as of optimization in an uncertain framework and iii) study in greater detail the effect of a possible stochastic exchange price.

A Appendix

A.1 Nash price bargaining

Let's consider the bargaining process leading to the definition of the energy price v_t on the basis of a mutually convenient agreement between seller and buyer when $p > q_t$. If, at the generic time period $t > 0$, the seller, S, and the buyer, B, agree on a certain energy price v_t, they will obtain the following payoffs, respectively:

$$W^S(v_t; q_t, p) = v_t, \quad \text{and} \quad W^B(v_t; q_t, p) = -v_t$$

If either party decides to quit the negotiation, the buyer's and the seller's outside payoffs would be:

$$\underline{W}^S(v_t; q_t, p) = q_t \quad \text{and} \quad \underline{W}^B(v_t; q_t, p) = -p$$

Assume now that S and B engage in a Nash Bargaining game with outside options. As standard, this game can be solved using the Nash Bargaining solution concept (Nash (1950), Nash (1953), Harsanyi (1977)).
A feasible Nash Bargaining solution, v_t^* solves the following maximization problem:

$$\begin{aligned}\max_{v_t \geq 0} \Omega \quad &= \quad \Big(W^S(v_t; q_t, p) - \underline{W}^S(v_t; q_t, p)\Big)^m \cdot \Big(W^B(v_t; q_t, p) - \underline{W}^B(v_t; q_t, p)\Big)^{1-m} \\ \text{s.t.} \quad & W^S(v_t; q_t, p) \geq \underline{W}^S(v_t; q_t, p) \qquad \text{and} \\ & W^B(v_t; q_t, p) \leq \underline{W}^B(v_t; q_t, p) \end{aligned} \tag{A.1.1}$$

where by m and $1 - m$ with $m \in (0, 1)$ we denote the seller's and buyer's strength exerted in the bargaining.
The first-order Condition for the maximization problem (A.1.1) is: [39]

$$\left.\frac{d\Omega}{dv_t}\right|_{v_t = v_t^*} = (v_t^* - q_t)^{m-1}(p - v_t^*)^{-m}[v_t - mp - (1-m)q_t] = 0 \tag{A.1.2}$$

Solving Eq. (A.1.2) we obtain

$$v_t^* = m \cdot p + (1 - m) \cdot q_t \tag{A.1.3}$$

[39] where the second-order Condition holds always.

A.2 Expected energy cost under the PV project

The general solutions to the differential equations (11.1) and (12.1) are (see Dixit (1989) pp. 624-628):[40]

$$
\begin{aligned}
C_i^{NSCE}(q_t;\alpha_i) &= \frac{p}{r} - \alpha_i \frac{q_t}{r-\theta} + \widehat{X}_i^{NSCE} q_t^{\beta_2}, \quad \text{for} \quad q_t > p, && \text{(A.2.1)} \\
C_i^{SCE}(q_t;\alpha_i,\gamma_i,\gamma_j) &= \frac{p}{r} - \alpha_i \frac{q_t}{r-\theta} - S(q_t;\alpha_i,\gamma_i,\gamma_j)\left(\frac{p}{r} - \frac{q_t}{r-\theta}\right) \\
&\quad + \widehat{Y}_i^{SCE} q_t^{\beta_1}, \quad \text{for} \quad q_t < p, && \text{(A.2.2)}
\end{aligned}
$$

where $\beta_2 < 0$ and $\beta_1 > 1$ are the roots of the characteristic equation $\Phi(x) \equiv \frac{1}{2}\sigma^2 x(x-1) + \theta x - r$. The terms $\widehat{X}_i^{NSCE} q_t^{\beta_2}$ and $\widehat{Y}_i^{SCE} q_t^{\beta_1}$ represents the value associated with the option to switch to a regime reducing the total energy cost. Hence, to be consistent, the constants $\widehat{X}_i^{NSCE}$ and $\widehat{Y}_i^{SCE}$ must be non-positive. At $q_t = p$, the standard pair of Conditions for an optimal switching policy must hold, that is, the following:

value-matching Condition

$$
C_i^{NSCE}(p;\alpha_i) = C_i^{SCE}(p;\alpha_i,\gamma_i,\gamma_j), \tag{A.2.3}
$$

smooth-pasting Condition

$$
\left.\frac{dC_i^{NSCE}(q_t;\alpha_i)}{dq_t}\right|_{q_t=p} = \left.\frac{dC_i^{SCE}(q_t;\alpha_i,\gamma_i,\gamma_j)}{dq_t}\right|_{q_t=p}. \tag{A.2.4}
$$

Solving the program [A.2.3 - A.2.4] yields

$$
\begin{aligned}
\widehat{X}_i^{NSCE} &= S(q_t;\alpha_i,\gamma_i,\gamma_j)\frac{p}{r-\theta}\frac{r-\theta\beta_1}{r(\beta_2-\beta_1)}p^{-\beta_2} = S(q_t;\alpha_i,\gamma_i,\gamma_j)X^{NSCE}p^{-\beta_2} \\
\widehat{Y}_i^{SCE} &= S(q_t;\alpha_i,\gamma_i,\gamma_j)\frac{p}{r-\theta}\frac{r-\theta\beta_2}{r(\beta_2-\beta_1)}p^{-\beta_1} = S(q_t;\alpha_i,\gamma_i,\gamma_j)Y^{SCE}p^{-\beta_1}
\end{aligned}
$$

which are linear in α_i and α_j and non-positive.

[40]Note that the general solution to Eq. (11.1) should take the form

$$
C_i^{NSCE}(q_t;\alpha_i) = \frac{c}{r} - \frac{\alpha_i q_t}{r-\theta} + \widehat{X}_i^{NSCE} q_t^{\beta_2} + \widehat{Y}_i^{NSCE} q_t^{\beta_1}.
$$

However, since the value of the option to switch to the regime contemplating self-consumption vanishes as $q_t \to \infty$, we then set $\widehat{Y}_i^{NSCE} = 0$. Similarly, the general solution to Eq. (12.1) should be

$$
C_i^{SCE}(q_t;\xi_i,\alpha_i) = \frac{(1-\xi_i\alpha_i)p}{r} - \frac{(1-\xi_i)\alpha_i q_t}{r-\theta} + \widehat{X}_i^{SCE} q_t^{\beta_2} + \widehat{Y}_i^{SCE} q_t^{\beta_1}.
$$

However, the option to switch to the regime where all the energy produced is sold becomes valueless as $q_t \to 0$ and then we set $\widehat{X}_i^{SCE} = 0$.

A.3 The value of the PV investment project

Let's prove that

$$\Delta C_i\left(q_t;\alpha_i,\gamma_i,\gamma_j\right)=\frac{p}{r}-C_i\left(q_t;\alpha_i,\gamma_i,\gamma_j\right)>0,\quad \text{for any } q_t<p \tag{A.3.1}$$

Substituting Eq.(15) into the inequality (A.3.1) yields:

$$\alpha_i\frac{q_t}{r-\theta}+S\left(q_t;\alpha_i,\gamma_i,\gamma_j\right)H\left(q_t\right)>0 \tag{A.3.2}$$

where

$$H\left(q_t\right)=\left(\frac{p}{r}-\frac{q_t}{r-\theta}\right)-Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}. \tag{A.3.3}$$

Note that

i) $H\left(0\right)=\frac{p}{r}>0$,

ii) $H\left(p\right)=\frac{p}{r}\frac{r-\beta_1\theta}{(r-\theta)(\beta_1-\beta_2)}>0$,

iii) $H\left(0\right)>H\left(p\right)$, and

iv) $\frac{d^2H(q_t)}{dq_t^2}=\frac{\beta_1(\beta_1-1)}{r-\theta}\frac{r-\theta\beta_2}{r(\beta_1-\beta_2)}\left(\frac{q_t}{p}\right)^{\beta_1-2}\frac{1}{p}>0.$

Hence, in order to prove that $H\left(q_t\right)>0$ and, consequently, $\Delta C_i\left(q_t;\alpha_i,\gamma_i,\gamma_j\right)>0$ it suffices showing that the first derivative of $H\left(q_t\right)$, i.e.,

$$\frac{dH\left(q_t\right)}{dq_t}=-\frac{1}{r-\theta}-\frac{\beta}{r-\theta}\frac{r-\theta\beta_2}{r\left(\beta_2-\beta_1\right)}\left(\frac{q_t}{p}\right)^{\beta_1-1}$$

takes a negative sign at both $q_t=0$ and $q_t=p$, which, as shown in the following, is always the case:

$$\left.\frac{dH\left(q_t\right)}{dq_t}\right|_{q_t=0}=-\frac{1}{r-\theta}<0$$

$$\left.\frac{dH\left(q_t\right)}{dq_t}\right|_{q_t=p}=\frac{\beta_2}{r-\theta}\frac{r-\beta_1\theta}{r(\beta_1-\beta_2)}<0$$

A.4 The EC energy exchange scenarios

A.4.1 Scenario 1: excess supply in the EC energy exchange

Suppose that:

$$0 < (1-\bar{b}) - \xi_1\alpha_1 < (1-\xi_2)\alpha_2, \tag{A.4.1}$$
$$0 < (1-\bar{b}) - \xi_2\alpha_2 < (1-\xi_1)\alpha_1. \tag{A.4.2}$$

When $q_t < p$, as the EC exchange is more convenient than trading energy with N, the two prosumers exchange the following quantities of energy:

$$\gamma_1 = (1-\bar{b}) - \xi_1\alpha_1, \tag{A.4.3}$$
$$\gamma_2 = (1-\bar{b}) - \xi_2\alpha_2. \tag{A.4.4}$$

As for the individual excess supply, each prosumer has no other alternative than selling this energy to N at price q_t.
Substituting Eqs. (A.4.3) and (A.4.4) into Eq. (20) and solving Problem (19) yields:

$$\alpha_1^* = \alpha_2^* = \alpha^* = \frac{1}{K_B}\frac{q_t}{r-\theta} > 0. \tag{A.4.5}$$

The optimal pair (α_1^*, α_2^*) must be consistent with the feasibility constraints (A.4.3) and (A.4.4). As it can be easily shown, this requires that the following restrictions:

$$-(1-\frac{1-\bar{b}}{\alpha^*}) < (\xi_1-\xi_2) < 1-\frac{1-\bar{b}}{\alpha^*}, \tag{A.4.6.1}$$
$$\xi_1\alpha^* + \bar{b} < 1, \tag{A.4.6.2}$$
$$\xi_2\alpha^* + \bar{b} < 1, \tag{A.4.6.3}$$
$$\alpha^* + \bar{b} > 1, \tag{A.4.6.4}$$

hold together, otherwise, the pair (α_1^*, α_2^*) is not feasible. Last, substituting Eq. (A.4.5) into (20) yields the expected net present value of the PV project, that is:

$$O(\alpha_1^*, \alpha_2^*) = \alpha^{*2}K_B + 2(1-\bar{b})\left[\frac{p}{r} - \frac{q_t}{r-\theta} - Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right] - K_A. \tag{A.4.7}$$

A.4.2 Scenario 2: excess demand in the EC energy exchange

Suppose that:

$$(1-\bar{b}) - \xi_1\alpha_1 \geq (1-\xi_2)\alpha_2 > 0, \quad \text{(A.4.8)}$$
$$(1-\bar{b}) - \xi_2\alpha_2 \geq (1-\xi_1)\alpha_1 > 0. \quad \text{(A.4.9)}$$

Internal solution. Let's start by considering the case where

$$(1-\bar{b}) - \xi_1\alpha_1 > (1-\xi_2)\alpha_2 > 0, \quad \text{(A.4.10)}$$
$$(1-\bar{b}) - \xi_2\alpha_2 > (1-\xi_1)\alpha_1 > 0. \quad \text{(A.4.11)}$$

When $q_t < p$, as the EC exchange is more convenient than trading energy with N, the two prosumers exchange the following quantities of energy:

$$\gamma_1 = (1-\xi_2)\alpha_2, \quad \text{(A.4.12)}$$
$$\gamma_2 = (1-\xi_1)\alpha_1. \quad \text{(A.4.13)}$$

As for the excess demand, each prosumer has no other alternative than purchasing energy from N at price p.
Substituting Eqs. (A.4.12) and (A.4.13) into (20) and solving Problem (19) yields:[41]

$$\alpha_1^* = \alpha_2^* = \alpha^* = \frac{1}{K_B}\left[\frac{p}{r} - Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right] > 0. \quad \text{(A.4.14)}$$

At (α_1^*, α_2^*), to be consistent with the feasibility constraints (A.4.8) and (A.4.9), the following restrictions:

$$-(\frac{1-\bar{b}}{\alpha^*} - 1) < (\xi_1 - \xi_2) < \frac{1-\bar{b}}{\alpha^*} - 1 \quad \text{(A.4.15.1)}$$
$$\alpha^* + \bar{b} < 1, \quad \text{(A.4.15.2)}$$

must hold together, otherwise, the solution is not feasible.
Last, under this scenario, the expected net present value of the PV project is equal to:

$$O\left(\alpha_1^*, \alpha_2^*\right) = \alpha^{*2}K_B - K_A. \quad \text{(A.4.16)}$$

Corner solution 1. Consider the case where

$$(1-\bar{b}) - \xi_1\alpha_1 > (1-\xi_2)\alpha_2 > 0, \quad \text{(A.4.17)}$$
$$(1-\bar{b}) - \xi_2\alpha_2 = (1-\xi_1)\alpha_1 > 0. \quad \text{(A.4.18)}$$

Combining Inequality (A.4.17) and Eq. (A.4.18) yields

$$\alpha_1 = \frac{(1-\bar{b}) - \xi_2\alpha_2}{1-\xi_1}, \quad \text{(A.4.19)}$$
$$\alpha_1 + \alpha_2 < 2(1-\bar{b}). \quad \text{(A.4.20)}$$

[41] We show in Appendix A.3 that $\frac{p}{r} - Y^{SCE}(\frac{q_t}{p})^{\beta} > \frac{q_t}{r-\theta} \geq 0$ when $q_t < p$.

Prosumer 1 and prosumer 2 find convenient exchanging the following amounts of energy:

$$\gamma_1 = (1-\xi_2)\alpha_2, \quad (A.4.21)$$

$$\gamma_2 = (1-\xi_1)\alpha_1, \quad (A.4.22)$$

respectively. Substituting Eqs. (A.4.21) and (A.4.22) into $O(\alpha_1, \alpha_2)$ and solving Problem (19) yields:

$$\alpha_1^* = \frac{(1-\bar{b})(1-\xi_1)}{(1-\xi_1)^2+\xi_2^2} - \frac{\xi_2(1-\xi_1-\xi_2)}{(1-\xi_1)^2+\xi_2^2}\frac{\frac{p}{r} - Y^{SCE}(\frac{q_t}{p})^{\beta_1}}{K_B}, \quad (A.4.23)$$

$$\alpha_2^* = \frac{(1-\bar{b})\xi_2}{(1-\xi_1)^2+\xi_2^2} + \frac{(1-\xi_1)(1-\xi_1-\xi_2)}{(1-\xi_1)^2+\xi_2^2}\frac{\frac{p}{r} - Y^{SCE}(\frac{q_t}{p})^{\beta_1}}{K_B}. \quad (A.4.24)$$

The feasibility of the optimal pair (α_1^*, α_2^*) requires that the following restrictions:

$$\alpha_1^* > 0, \quad (A.4.25.1)$$

$$\alpha_2^* > 0, \quad (A.4.25.2)$$

$$\alpha_1^* + \alpha_2^* < 2(1-\bar{b}), \quad (A.4.25.3)$$

hold together, otherwise, the pair (α_1^*, α_2^*) is not feasible. Under this scenario, the expected net present value of the PV project is equal to:

$$O(\alpha_1^*, \alpha_2^*) = (\alpha_1^* + \alpha_2^*)\left[\frac{p}{r} - Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right] - I(\alpha_1^*, \alpha_2^*). \quad (A.4.26)$$

Corner solution 2. Suppose that

$$(1-\bar{b}) - \xi_1\alpha_1 = (1-\xi_2)\alpha_2 > 0, \quad (A.4.27)$$

$$(1-\bar{b}) - \xi_2\alpha_2 > (1-\xi_1)\alpha_1 > 0. \quad (A.4.28)$$

Combining Eq. (A.4.27) and Inequality (A.4.27) yields

$$\alpha_2 = \frac{(1-\bar{b}) - \xi_1\alpha_1}{(1-\xi_2)}, \quad (A.4.29)$$

$$\alpha_1 + \alpha_2 < 2(1-\bar{b}). \quad (A.4.30)$$

Prosumer 1 and prosumer 2 find convenient exchanging the following amounts of energy:

$$\gamma_1 = (1-\xi_2)\alpha_2, \quad (A.4.31)$$

$$\gamma_2 = (1-\xi_1)\alpha_1, \quad (A.4.32)$$

respectively. Substituting Eqs. (A.4.31) and (A.4.32) into $O(\alpha_1, \alpha_2)$ and solving Problem (19) yields:

$$\alpha_1^* = \frac{(1-\bar{b})\xi_1}{(1-\xi_2)^2+\xi_1^2} + \frac{(1-\xi_2)(1-\xi_1-\xi_2)}{(1-\xi_2)^2+\xi_1^2}\frac{\frac{p}{r} - Y^{SCE}(\frac{q_t}{p})^{\beta_1}}{K_B}, \quad (A.4.33)$$

$$\alpha_2^* = \frac{(1-\bar{b})(1-\xi_2)}{(1-\xi_2)^2+\xi_1^2} - \frac{\xi_1(1-\xi_1-\xi_2)}{(1-\xi_2)^2+\xi_1^2}\frac{\frac{p}{r} - Y^{SCE}(\frac{q_t}{p})^{\beta_1}}{K_B}. \quad (A.4.34)$$

The feasibility of the optimal pair (α_1^*, α_2^*) requires that the following restrictions:

$$\alpha_1^* > 0, \quad \text{(A.4.35.1)}$$
$$\alpha_2^* > 0, \quad \text{(A.4.35.2)}$$
$$\alpha_1^* + \alpha_2^* < 2(1-\bar{b}), \quad \text{(A.4.35.3)}$$

hold together, otherwise, the pair (α_1^*, α_2^*) is not feasible. Under this scenario, the expected net present value of the PV project is equal to:

$$O(\alpha_1^*, \alpha_2^*) = (\alpha_1^* + \alpha_2^*)\left[\frac{p}{r} - Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right] - I(\alpha_1^*, \alpha_2^*). \quad \text{(A.4.36)}$$

Corner solution 3. Suppose that

$$(1-\bar{b}) - \xi_1\alpha_1 = (1-\xi_2)\alpha_2, \quad \text{(A.4.37)}$$
$$(1-\bar{b}) - \xi_2\alpha_2 = (1-\xi_1)\alpha_1. \quad \text{(A.4.38)}$$

Solving the System [A.4.37-A.4.38] yields

$$\alpha_1^* = (1-\bar{b})\frac{1-2\xi_2}{1-\xi_2-\xi_1}, \quad \text{(A.4.39)}$$
$$\alpha_2^* = (1-\bar{b})\frac{1-2\xi_1}{1-\xi_2-\xi_1}. \quad \text{(A.4.40)}$$

The following restrictions are needed in order to secure that $\alpha_1^* > 0$ and $\alpha_2^* > 0$:

$$\xi_1 + \xi_2 < 1, \quad \xi_1 < 1/2, \quad \xi_2 < 1/2, \quad \text{(A.4.41.1)}$$
$$\xi_1 + \xi_2 > 1, \quad \xi_1 > 1/2, \quad \xi_2 > 1/2. \quad \text{(A.4.41.2)}$$

Last, under this scenario, the expected net present value of the PV project is equal to:

$$O(\alpha_1^*, \alpha_2^*) = 2(1-\bar{b})\left[\frac{p}{r} - Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right] - I(\alpha_1^*, \alpha_2^*). \quad \text{(A.4.42)}$$

A.4.3 Scenario 3: non complementarity in the EC exchange

Suppose that:

$$0 < (1-\bar{b}) - \xi_1\alpha_1 < (1-\xi_2)\alpha_2, \tag{A.4.43}$$
$$(1-\bar{b}) - \xi_2\alpha_2 \geq (1-\xi_1)\alpha_1 > 0. \tag{A.4.44}$$

Internal solution. Consider the case where:

$$0 < (1-\bar{b}) - \xi_1\alpha_1 < (1-\xi_2)\alpha_2, \tag{A.4.45}$$
$$(1-\bar{b}) - \xi_2\alpha_2 > (1-\xi_1)\alpha_1 > 0. \tag{A.4.46}$$

Prosumer 1 and prosumer 2 find convenient exchanging the following quantitites of energy:

$$\gamma_1 = (1-\bar{b}) - \xi_1\alpha_1, \tag{A.4.47}$$
$$\gamma_2 = (1-\xi_1)\alpha_1, \tag{A.4.48}$$

respectively. Prosumer 2 will then sell the residual quantity of energy, $(1-\xi_2)\alpha_2-(1-\bar{b})-\xi_1\alpha_1$, to N at price q_t and purchase the quantity of energy $(1-\bar{b})-\xi_2\alpha_2-\alpha_1(1-\xi_1)$ from N at price p.
Substituting Eqs. (A.4.47) and (A.4.48) into Eq. (20) and solving Problem (19) yields:

$$\alpha_1^* = \frac{1}{K_B}\left\{\xi_1\frac{q_t}{r-\theta} + (1-\xi_1)\left[\frac{p}{r} - Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right]\right\} > 0, \tag{A.4.49}$$
$$\alpha_2^* = \frac{1}{K_B}\left\{(1-\xi_2)\frac{q_t}{r-\theta} + \xi_2\left[\frac{p}{r} - Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right]\right\} > 0. \tag{A.4.50}$$

The feasibility of the optimal pair (α_1^*, α_2^*) requires that the following restrictions:

$$(1-\bar{b}) < \xi_1\alpha_1^* + (1-\xi_2)\alpha_2^*, \tag{A.4.51.1}$$
$$(1-\bar{b}) > (1-\xi_1)\alpha_1^* + \xi_2\alpha_2^*, \tag{A.4.51.2}$$
$$\xi_1\alpha_1^* + \bar{b} < 1, \tag{A.4.51.3}$$

hold together, otherwise, the pair (α_1^*, α_2^*) is not feasible.
Last, under this scenario, the expected net present value of the PV project is equal to:

$$O(\alpha_1^*, \alpha_2^*) = \frac{K_B}{2}(\alpha_1^{*2} + \alpha_2^{*2}) + (1-\bar{b})\left[\frac{p}{r} - \frac{q_t}{r-\theta} - Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right] - K_A. \tag{A.4.52}$$

Corner solution. Suppose that

$$0 < (1-\bar{b}) - \xi_1\alpha_1 < (1-\xi_2)\alpha_2, \tag{A.4.53}$$
$$(1-\bar{b}) - \xi_2\alpha_2 = (1-\xi_1)\alpha_1 > 0. \tag{A.4.54}$$

Combining Inequality (A.4.53) and Eq. (A.4.54) yields

$$\alpha_1 = \frac{(1-\bar{b}) - \xi_2\alpha_2}{1-\xi_1}, \tag{A.4.55}$$
$$\alpha_1 + \alpha_2 > 2(1-\bar{b}). \tag{A.4.56}$$

Prosumer 1 and prosumer 2 find convenient exchanging the following quantities of energy:

$$\gamma_1 = (1-\bar{b}) - \xi_1\alpha_1, \tag{A.4.57}$$

$$\gamma_2 = (1-\bar{b}) - \xi_2\alpha_2, \tag{A.4.58}$$

respectively. Substituting Eqs. (A.4.57) and (A.4.58) into $O(\alpha_1, \alpha_2)$ and solving Problem (19) yields:

$$\alpha_1^* = \frac{(1-\bar{b})(1-\xi_1)}{(1-\xi_1)^2+\xi_2^2} - \frac{\xi_2(1-\xi_1-\xi_2)}{(1-\xi_1)^2+\xi_2^2}\frac{\frac{q_t}{r-\theta}}{K_B}, \tag{A.4.59}$$

$$\alpha_2^* = \frac{(1-\bar{b})\xi_2}{(1-\xi_1)^2+\xi_2^2} + \frac{(1-\xi_1)(1-\xi_1-\xi_2)}{(1-\xi_1)^2+\xi_2^2}\frac{\frac{q_t}{r-\theta}}{K_B}. \tag{A.4.60}$$

The feasibility of the optimal pair (α_1^*, α_2^*) requires that the following restrictions:

$$\alpha_1^* > 0,$$
$$\xi_1\alpha_1^* + \bar{b} < 1,$$
$$\alpha_1^* + \alpha_2^* > 2(1-\bar{b}),$$

hold together, otherwise, the pair (α_1^*, α_2^*) is not feasible. Under this scenario, the expected net present value of the PV project is equal to:

$$O(\alpha_1^*, \alpha_2^*) = (\alpha_1^*+\alpha_2^*)\frac{q_t}{r-\theta} - I(\alpha_1^*, \alpha_2^*) + 2(1-\bar{b})\left[\frac{p}{r} - \frac{q_t}{r-\theta} - Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right]. \tag{A.4.61}$$

A.4.4 Scenario 4: non complementarity in the EC exchange

Suppose that:

$$(1-\bar{b}) - \xi_1\alpha_1 \geq (1-\xi_2)\alpha_2 > 0, \quad \text{(A.4.62)}$$

$$0 < (1-\bar{b}) - \xi_2\alpha_2 < (1-\xi_1)\alpha_1. \quad \text{(A.4.63)}$$

Internal solution. Consider the case where:

$$(1-\bar{b}) - \xi_1\alpha_1 > (1-\xi_2)\alpha_2 > 0, \quad \text{(A.4.64)}$$

$$0 < (1-\bar{b}) - \xi_2\alpha_2 < (1-\xi_1)\alpha_1. \quad \text{(A.4.65)}$$

Prosumer 1 and prosumer 2 find convenient exchanging the following quantities of energy:

$$\gamma_1 = (1-\xi_2)\alpha_2 \quad \text{(A.4.66)}$$

$$\gamma_2 = (1-\bar{b}) - \xi_2\alpha_2 \quad \text{(A.4.67)}$$

Substituting Eqs. (A.4.66) and (A.4.67) into (20) and solving Problem (19) yields:

$$\alpha_1^* = \frac{1}{K_B}\left\{(1-\xi_1)\frac{q_t}{r-\theta} + \xi_1\left[\frac{p}{r} - Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right]\right\} > 0 \quad \text{(A.4.68)}$$

$$\alpha_2^* = \frac{1}{K_B}\left\{\xi_2\frac{q_t}{r-\theta} + (1-\xi_2)\left[\frac{p}{r} - Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right]\right\} > 0 \quad \text{(A.4.69)}$$

In order to have a feasible pair (α_1^*, α_2^*), the following restrictions

$$(1-\bar{b}) > \xi_1\alpha_1^* + (1-\xi_2)\alpha_2^* \quad \text{(A.4.70.1)}$$

$$(1-\bar{b}) < (1-\xi_1)\alpha_1^* + \xi_2\alpha_2^* \quad \text{(A.4.70.2)}$$

$$\xi_2\alpha_2^* + \bar{b} < 1 \quad \text{(A.4.70.3)}$$

must hold together, otherwise, the pair (α_1^*, α_2^*) is not feasible.
Last, substituting Eqs. (A.4.68) and (A.4.69) into (20) yields

$$O\left(\alpha_1^*, \alpha_2^*\right) = \frac{K_B}{2}(\alpha_1^{*2} + \alpha_2^{*2}) + (1-\bar{b})\left[\frac{p}{r} - \frac{q_t}{r-\theta} - Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right] - K_A. \quad \text{(A.4.71)}$$

Corner solution. Suppose that

$$(1-\bar{b}) - \xi_1\alpha_1 = (1-\xi_2)\alpha_2 > 0, \quad \text{(A.4.72)}$$

$$0 < (1-\bar{b}) - \xi_2\alpha_2 < (1-\xi_1)\alpha_1. \quad \text{(A.4.73)}$$

Combining Eq. (A.4.72) and Inequality (A.4.72) yields

$$\alpha_2 = \frac{(1-\bar{b}) - \xi_1\alpha_1}{(1-\xi_2)}, \quad \text{(A.4.74)}$$

$$\alpha_1 + \alpha_2 > 2(1-\bar{b}). \quad \text{(A.4.75)}$$

Prosumer 1 and prosumer 2 find convenient exchanging the following quantities of energy:

$$\gamma_1 = (1-\bar{b}) - \xi_1\alpha_1, \tag{A.4.76}$$

$$\gamma_2 = (1-\bar{b}) - \xi_2\alpha_2, \tag{A.4.77}$$

respectively. Substituting Eqs. (A.4.76) and (A.4.76) into $O(\alpha_1, \alpha_2)$ and solving Problem (19) yields:

$$\alpha_1^* = \frac{(1-\bar{b})\xi_1}{(1-\xi_2)^2+\xi_1^2} + \frac{(1-\xi_2)(1-\xi_1-\xi_2)}{(1-\xi_2)^2+\xi_1^2}\frac{\frac{q_t}{r-\theta}}{K_B}, \tag{A.4.78}$$

$$\alpha_2^* = \frac{(1-\bar{b})(1-\xi_2)}{(1-\xi_2)^2+\xi_1^2} - \frac{\xi_1(1-\xi_1-\xi_2)}{(1-\xi_2)^2+\xi_1^2}\frac{\frac{q_t}{r-\theta}}{K_B}. \tag{A.4.79}$$

The feasibility of the optimal pair (α_1^*, α_2^*) requires that the following restrictions:

$$\begin{aligned} \alpha_2^* &> 0, \\ \xi_2\alpha_2^* + \bar{b} &< 1, \\ \alpha_1^* + \alpha_2^* &> 2(1-\bar{b}), \end{aligned}$$

hold together, otherwise, the pair (α_1^*, α_2^*) is not feasible. Under this scenario, the expected net present value of the PV project is equal to:

$$\begin{aligned} O(\alpha_1^*, \alpha_2^*) = {} & (\alpha_1^* + \alpha_2^*)\frac{q_t}{r-\theta} - I(\alpha_1^*, \alpha_2^*) \\ & +2(1-\bar{b})\left[\frac{p}{r} - \frac{q_t}{r-\theta} - Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right]. \end{aligned} \tag{A.4.80}$$

A.5 Numerical results

A.5.1 Scenario 1: excess supply in the EC energy exchange.

In Figure 5, we include the Constraints (A.4.6.1), (A.4.6.2), (A.4.6.3) and (A.4.6.4). Then, we isolate the feasible area (in gray) as resulting from the consideration of those constraints. This leads, on the Y-axis, to the indication of the gap between the two self-consumption parameters ($\xi_1 - \xi_2$) that may secure the feasibility of the solution found.

Under this Scenario, both optimal capacities (α_1^*, α_2^*) (A.4.5) and the expected net present value of the PV project, $O(\alpha_1^*, \alpha_2^*)$, (A.4.7) do not depend on the prosumers' self-consumption levels (ξ_i). Based on the parameters chosen for our calibration, we find that $\alpha_1^* = \alpha_2^* = \alpha^* = 0.71$ MWh and $O(\alpha_1^*, \alpha_2^*) = 3301$ Euro, respectively (see Table 3).

The solution $\alpha^* = 0.71$ is feasible conditional on letting the gap between ξ_1 and ξ_2 range within ± 0.15. This implies that the prosumers' self-consumption profiles must not be too distant.

In general, the gap may be larger at it is, for instance, the case for $\alpha^* \in [0.60; 1.20]$, where it may range within $\pm$ 0.50. Further, we notice that when α^* is higher than 1.20, the allowed gap starts shrinking as the optimal capacity increases. Finally, Figure 6 shows the set of (ξ_1, ξ_2) satisfying the Constraints above when each prosumer install a capacity, α^*, equal to 0.71.[42]

The quantity of self-consumed energy ($\xi_i \alpha^*$) and exchanged energy (γ_i) are determined over some feasible ranges of ξ_1 and ξ_2 (marked in dark gray in Figure 6). The corresponding figures are presented in Table 4. As it can be immediately seen, the quantity of self-consumed energy and exchanged energy are negatively related.

Figures 7 and 8, show the effects of a reduction in q_t and $LCOE$ on the feasible pairs of the prosumers' self-consumption parameters, respectively. A decrease in the price paid for the energy sold to N lowers i) the optimal capacity, α^*, and ii) the expected net present value,[43] $O(\alpha_1^*, \alpha_2^*)$ (See Table 3). We notice also that, with respect to the benchmark case, the prosumers' self-consumption profiles must be closer[44]. However, the resulting set of (ξ_1, ξ_2) associated with a feasible solution allows for higher levels of self-consumption. A decrease in the $LCOE$, which implies, ceteris paribus, a lower cost of the PV project, makes convenient installing an higher capacity with respect to the benchmark and increases the expected net present value of the PV project. The feasible area widens in terms of allowed gap between ξ_1 and ξ_2 but their allowed maximum level decreases.

Finally, lowering the volatility level to $\sigma = 0.25$ affects only the expected net present value of the PV project which is lower than in the benchmark case.

[42] The set is obtained by letting each ξ_i ($i = 1, 2$) vary between 0 to 1. In block 1, we have the ξ_1 and ξ_2 such that $\xi_1 - \xi_2 < \left(1 - \frac{1-\bar{b}}{\alpha^*}\right)$ and satisfying Eq. (A.4.6.2) and (Eq. A.4.6.3) whereas in block 2 those such that $\xi_1 - \xi_2 > -\left(1 - \frac{1-\bar{b}}{\alpha^*}\right)$ and satisfying Eq. (A.4.6.2) and (Eq. A.4.6.3). Finally, block 3, resulting from the combination of both the first and the second block, shows and show the set of all the feasible (ξ_1, ξ_2).

[43] This is because the gains from energy sold to N are lower.

[44] As it can be also immediately seen in Figure 5.

Parameters	*Benchmark case*	$q_t = 54$	$\sigma = 0.25$	$LCOE = 70$
α^*	0.710	0.650	0.710	0.810
$O(\alpha_1^*, \alpha_2^*)$	3301	3194	3194	3509

Table 3: *Scenario 1* - Benchmark results and comparative statics.

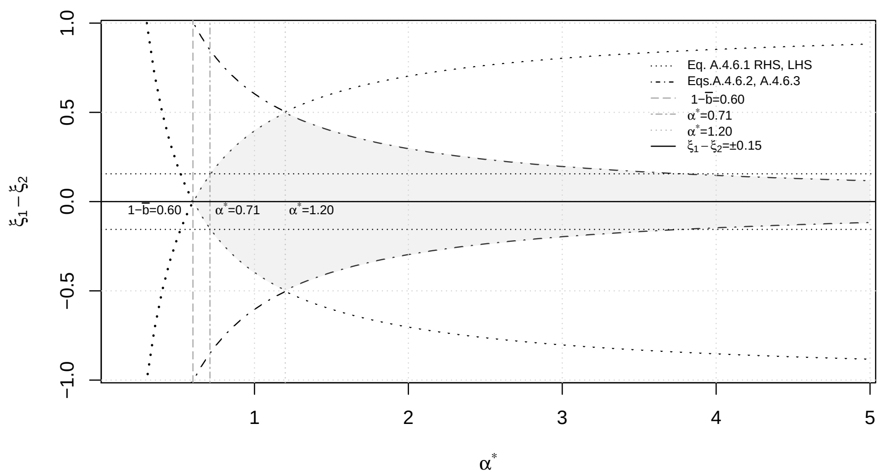

Figure 5: *Scenario 1* - The set of (ξ_1, ξ_2) associated with a feasible solution.

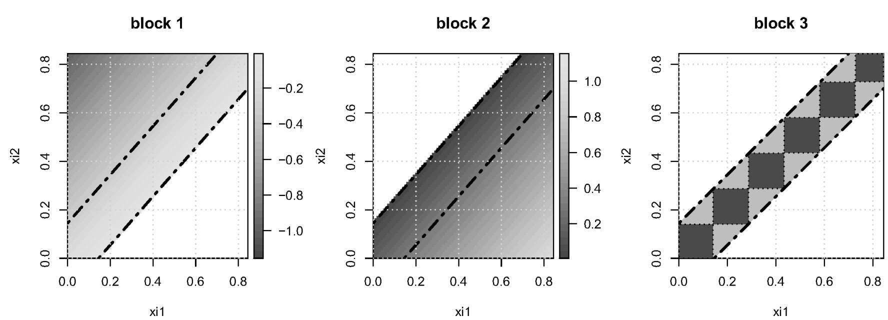

Figure 6: *Scenario 1* - The set of (ξ_1, ξ_2) associated with $\alpha^* = 0.71$.

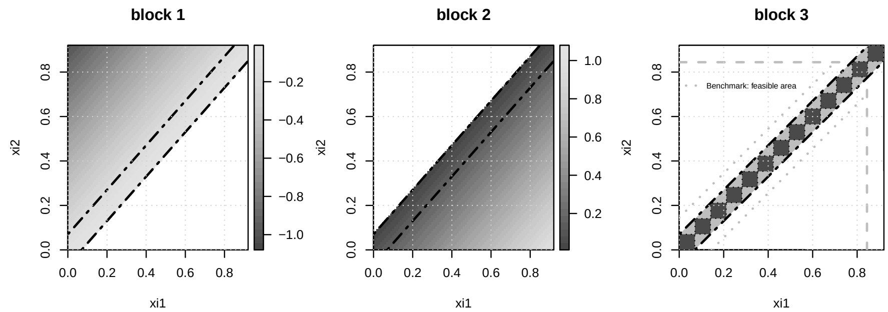

Figure 7: *Scenario 1* - The set of (ξ_1, ξ_2) associated with α^*: comparative statics on q.

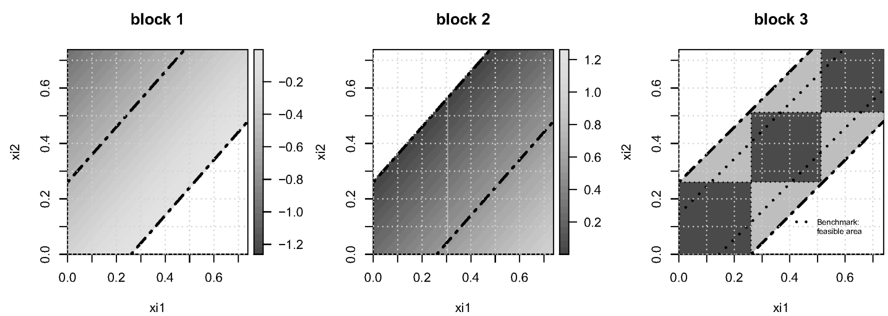

Figure 8: *Scenario 1* - The set of (ξ_1, ξ_2) associated with α^*: comparative statics on $LCOE$.

Parameters	FS1	FS2	FS3	FS4	FS5	FS6
$\xi_1, \xi_2 \in$	$[0; 0.14)$	$[0.14; 0.28)$	$[0.28; 0.43)$	$[0.43; 0.58)$	$[0.58; 0.72)$	$[0.72; 0.83]$
$\xi_1\alpha^*$	0.050	0.151	0.256	0.360	0.465	0.555
$\xi_2\alpha^*$	0.050	0.151	0.256	0.360	0.465	0.555
γ_1	0.550	0.448	0.344	0.240	0.136	0.045
γ_2	0.550	0.448	0.344	0.240	0.136	0.045

Table 4: *Scenario 1* - Self-consumed ($\xi_i\alpha^*$) and exchanged (γ_i) quantities of energy in the benchmark case over several feasible sets (FS) (dark gray squares in Figure 6).

A.5.2 Scenario 2: excess demand in the EC energy exchange

In Figure 9, we include the Constraints (A.4.15.1) and (A.4.15.2). Then, we isolate the feasible area (in gray) as resulting from the consideration of those constraints.

Under this Scenario, the optimal capacities, (α_1^*, α_2^*), (A.4.14) and the expected net present value of the project, $O(\alpha_1^*, \alpha_2^*)$, (A.4.16) do not depend on the prosumers' self-consumption levels (ξ_i). Based on the parameters chosen for our calibration, we find that $\alpha_1^* = \alpha_2^* = \alpha^* = 1.62$ MWh and $O(\alpha_1^*, \alpha_2^*) = 5647$ Euro, respectively (see Table 5).
As it can be immediately seen in Figure 9, the capacity level $\alpha^* = 1.62$ is not feasible. Thus, we move on considering the corner solutions (Appendix A.4).
Figures 10, 11 and 12 provide graphical representations of each set of scenario's constraints [45] and the resulting ranges of ξ_1 and ξ_2 associated with a feasible solution for each corner solution. The expected net present values of the PV project associated with each corner solution are presented in Figure 13.
Table 6 summarizes the findings associated with each corner solution.
In corner solution 1, the sets of ξ_1 and ξ_2 which allows reaching the highest level of expected net present value are $\xi_1 \in [0.30, 0.53]$ and $\xi_2 \in [0.52, 0.70]$. When considering instead corner solution 2, we have $\xi_1 \in [0.52, 0.70]$ and $\xi_2 \in [0.30, 0.53]$. In both cases, we notice that i) one prosumer must be more self-consumption oriented than the other, i) the average expected net present value is lower than under Scenario 1, iii) a lower q_t or a lower σ widens the feasible area, whereas a decrease in $LCOE$ shrinks it, but these changes do not affect the sets ξ_1 and ξ_2 which allows reaching the highest level of expected net present value.
The impact of changes in q_t, σ and $LCOE$ when considering the corner solution 1 are presented in Figures 14, 15, 16, respectively. [46]

In corner solution 3, the sets of ξ_1 and ξ_2 associated with a feasible solution are $\xi_1, \xi_2 \in [0; 0.50)$ (Eq. A.4.41.1) and $\xi_1, \xi_2 \in (0.50; 1]$ (Eq. A.4.41.2) (see Figure 12). This implies that, with respect to Scenario 1, the prosumers' self-consumption profile are allowed to be more than distant.

Parameters	*Benchmark case*	$q_t = 54$	$\sigma = 0.25$	$LCOE = 70$
α^*	1.620	1.590	1.550	1.850
$O(\alpha_1^*, \alpha_2^*)$	5647	5420	5146	6546

Table 5: *Scenario 2* - Benchmark results and comparative statics

[45] where the first and second blocks represent also the prosumers' optimal capacities
[46] For the sake of brevity, we do not present the comparative statics relative to corner solution 2 since they are specular to those relative to corner solution 1.

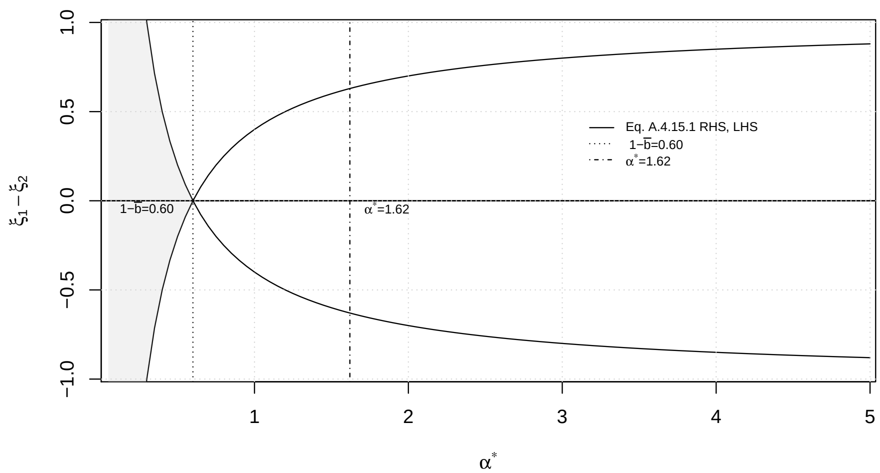

Figure 9: *Scenario 2* - The set of (ξ_1, ξ_2) associated with a feasible solution.

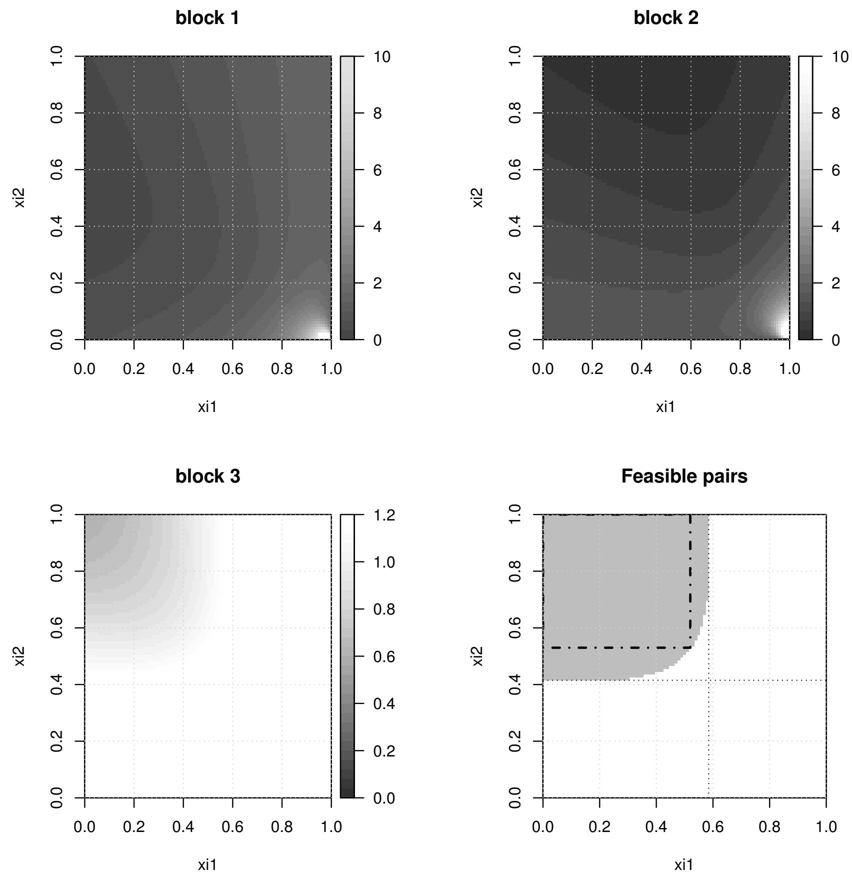

Figure 10: *Scenario 2* - Corner solution 1: constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution. Blocks 1 and 2 results from considering Eqs. (A.4.25.1) and (A.4.25.2) respectively. Block 3 results from considering Eq. (A.4.25.3). The last block shows the pairs of ξ_1 and ξ_2 associated with the optimal solution.

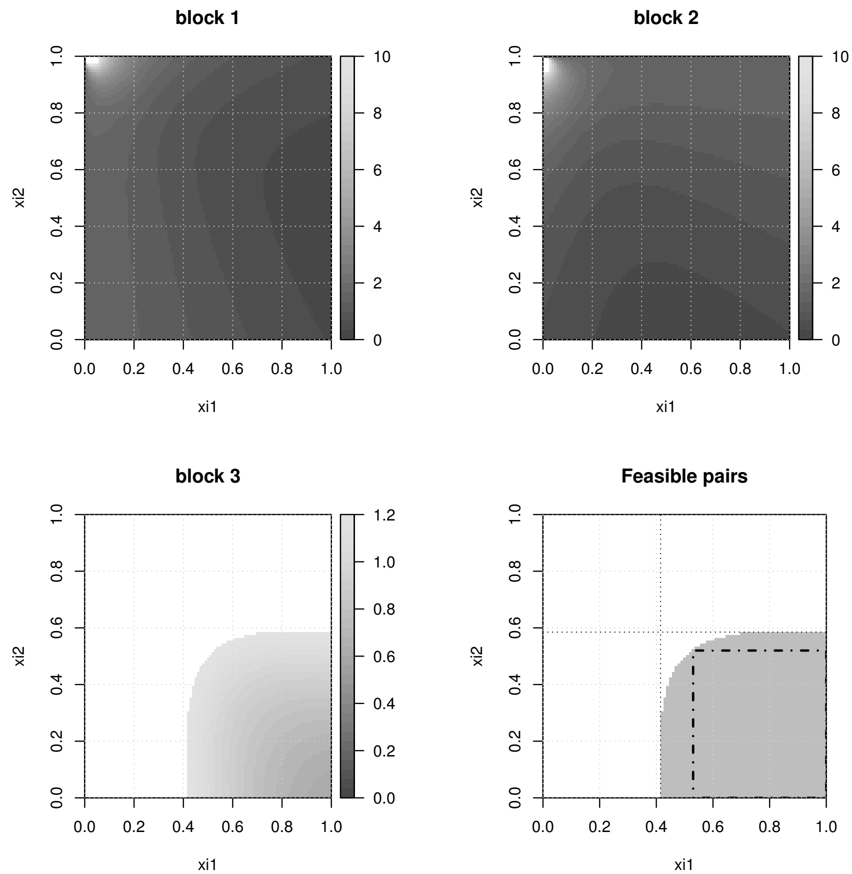

Figure 11: *Scenario 2* - Corner solution 2: constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution. Blocks 1 and 2 results from considering Eqs. (A.4.35.1) and (A.4.35.2), respectively. Block 3 results from considering Eq. (A.4.35.3). The last block shows the pairs of ξ_1 and ξ_2 associated with the optimal solution.

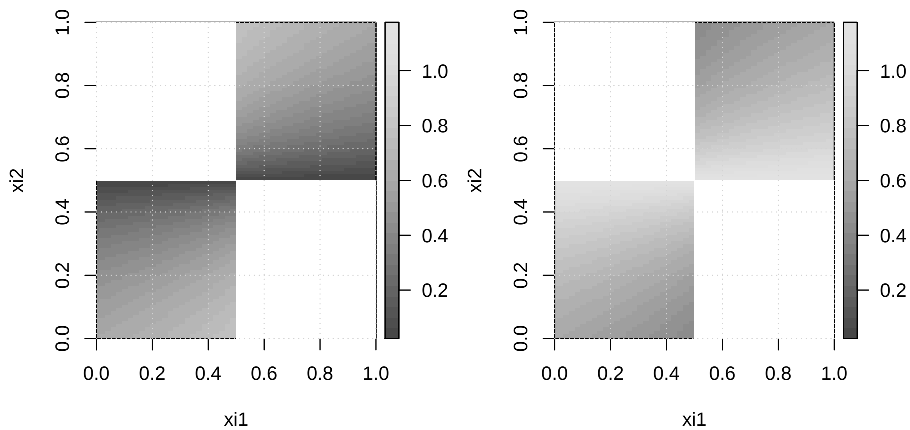

Figure 12: *Scenario 2* - Corner solution 3: constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution. Blocks 1 and 2 results from considering Eqs. (A.4.37) and (A.4.38), respectively.

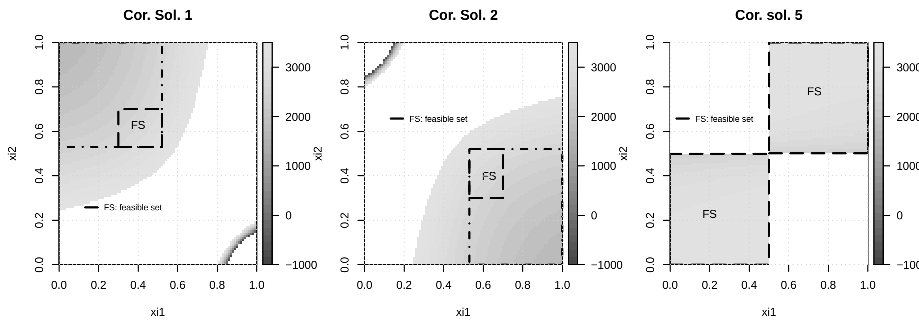

Figure 13: *Scenario 2* - Expected net present values. Blocks 1, 2 and 3 refer to corner solution 1,2 and 3 respectively. The feasible sets (FS) are identified considering only the pairs of the ξ_i associated with the highest level of expected net present value.

Parameters	*Cor. sol. 1*	*Cor. sol. 2*	*Cor. sol. 3*	*Cor. sol. 3*
$\xi_1 \in$	$[0.30; 0.53]$	$[0.52; 0.70]$	$[0; 0.50)$	$(0.50; 1]$
$\xi_2 \in$	$[0.52; 0.70]$	$[0.30; 0.53]$	$[0; 0.50)$	$(0.50; 1]$
α_1^*	0.535	0.488	0.600	0.600
α_2^*	0.488	0.535	0.600	0.600
$\xi_1\alpha_1^*$	0.228	0.295	0.174	0.426
$\xi_2\alpha_2^*$	0.294	0.229	0.174	0.426
γ_1^*	0.194	0.305	0.426	0.173
γ_2^*	0.306	0.194	0.426	0.173
$\mathcal{O}\left(\alpha_1^*, \alpha_2^*\right)$	2823	2823	3098	3098

Table 6: *Scenario 2* - Main findings by Corner solution

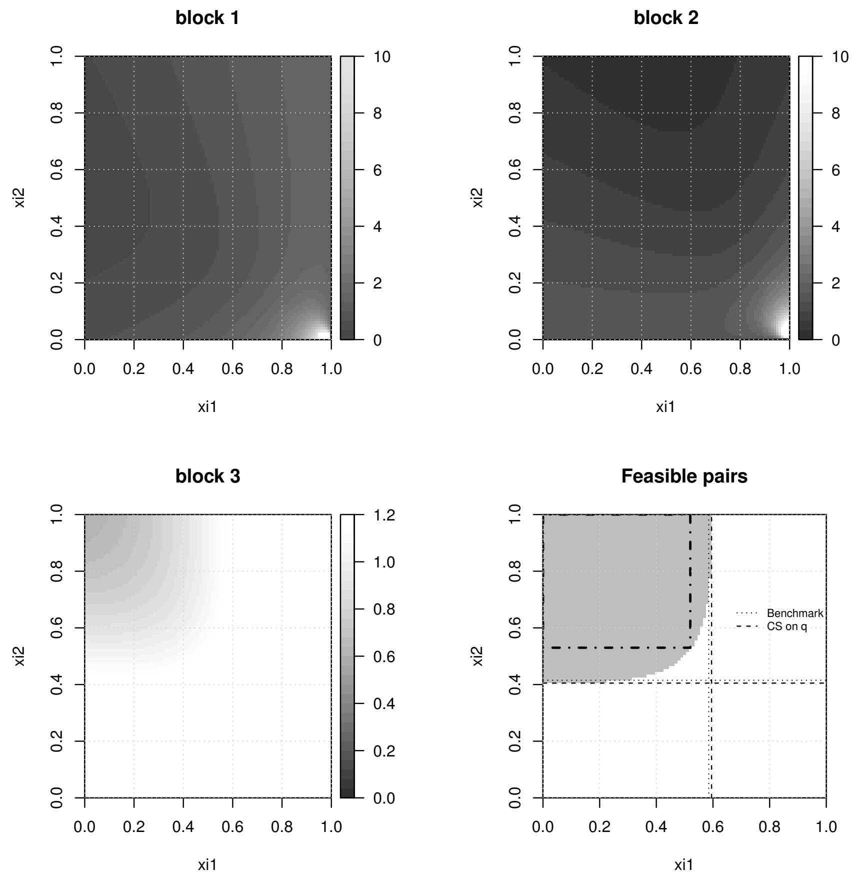

Figure 14: *Scenario 2* - Corner solution 1: constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution when $q_t = 54$.

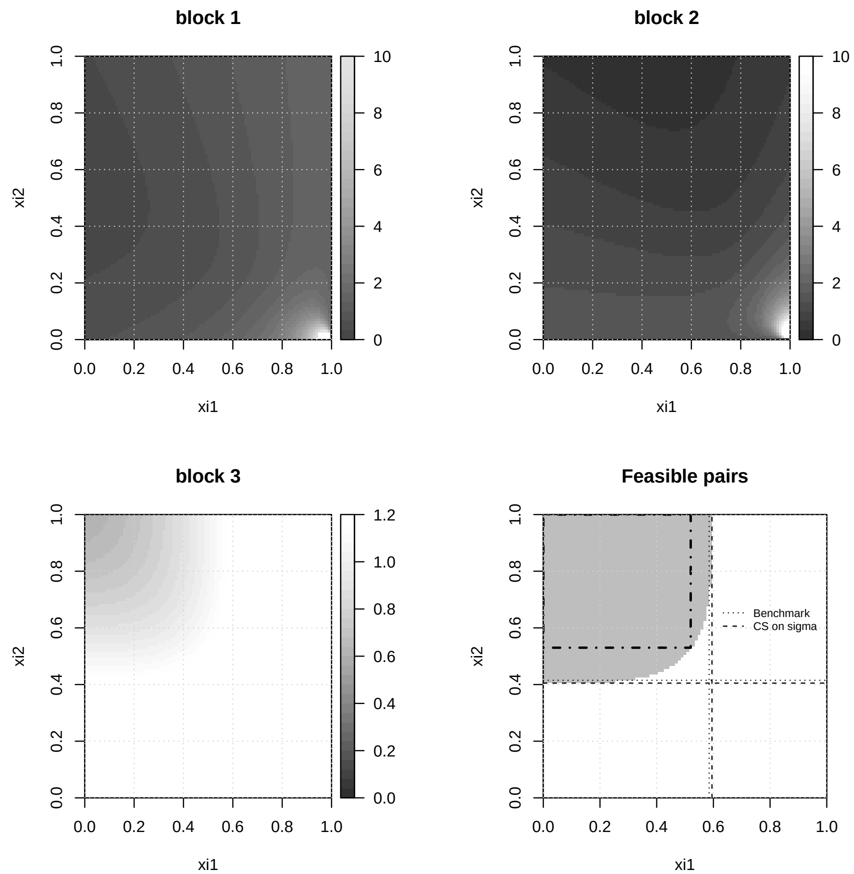

Figure 15: *Scenario 2* - Corner solution 1: constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution when $\sigma = 0.25$.

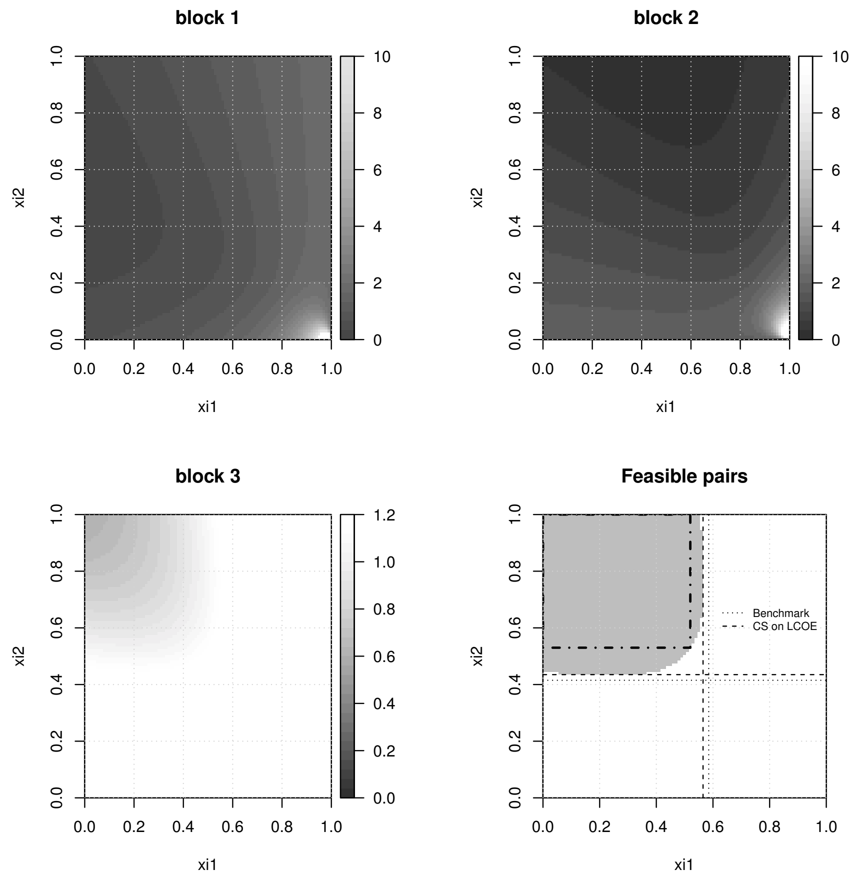

Figure 16: *Scenario 2* - Corner solution 1: constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution when $LCOE = 70$.

A.5.3 Scenario 3: non complementarity in the EC exchange

Under this Scenario, the optimal capacities, (α_1^*, α_2^*) (A.4.49,A.4.50) and the expected net present value of the project, $O(\alpha_1^*, \alpha_2^*)$, (A.4.52) depend on the prosumers' self-consumption levels (ξ_i).
In Figure 17, we include the scenario's constraints as a function of ξ_1 and ξ_2, with the aim to identify the ranges over which they are all satisfied. [47] The area satisfying the constraint (A.4.51.2) satisfies also constraint (A.4.51.1). The Constraint (A.4.51.3) is satisfied if ξ_1 ranges from 0 to 0.53 (gray area). The fourth block of the Figure 17 shows the set of ξ_i associated with a feasible solution, that is $\xi_1 \in [0.51; 0.52]$ and $\xi_2 \in [0; 0.02]$. This means that the scenario's constraints are satisfied only when prosumer 1 has a relatively high level of *self-consumption* while prosumers 2 has an almost null level of *self-consumption*.

Figures 18,19 and 20 present how scenario's feasible ranges vary in response to a decrease in q_t, in σ and in $LCOE$, respectively.
Table 7 shows the optimal capacities, the quantity of self-consumed energy, the quantity of exchanged energy and the expected net present values in the benchmark case and when allowing for a change in q_t, in σ and in $LCOE$.
A reduction in q_t widens the set of the pairs of the ξ_i associated with an optimal solution, allowing prosumer 1 to reach higher levels of self-consumption. Further, the optimal capacities decrease, prosumer 1 self consumes less while prosumer 2 self consumes more. The effect on exchanged quantities is the opposite. Overall, prosumers gain less from investing in the PV project.
A decrease in σ widens the the set of the pairs of the ξ_i associated with an optimal solution. The capacity installed by prosumer 2 increases, whereas the one installed by prosumer 1 decreases. The same occurs for self-consumption, while exchanged volume increases for prosumer 1 and decreases for prosumer 2. Also in this case, prosumers gain less from investing in the PV project.
Finally, any feasible solution may be found when lowering the $LCOE$ to 70.

[47] Eq. (A.4.51.1) in block 1, (A.4.51.2) in block 2 and (A.4.51.3) in block 3.
Constraints presented in Eq. (A.4.51.1) and (A.4.51.2) have been respectively rearranged as follow: $\xi_1\alpha_1^* + (1-\xi_2)\,\alpha_2^* - \left(1-\bar{b}\right) > 0$ and $(1-\xi_1)\,\alpha_1^* + \xi_2\alpha_2^* - \left(1-\bar{b}\right) < 0$. The constraints' graphical representation is obtained by letting ξ_1 and ξ_2 vary over the range from 0 to 1.

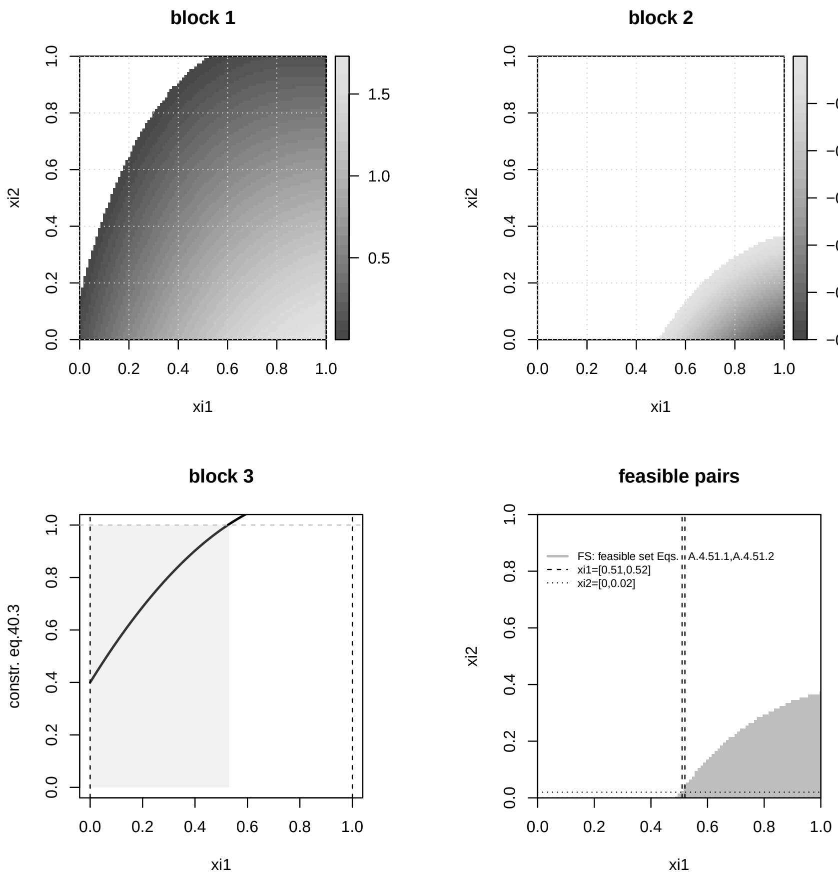

Figure 17: *Scenario 3* - Constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution. Block 1 results from considering Eq. (A.4.51.1), block 2 results from considering Eq. (A.4.51.2) and block 3 results from considering Eq. (A.4.51.3). Block 4 shows the pairs of ξ_1 and ξ_2 associated with the optimal solution.

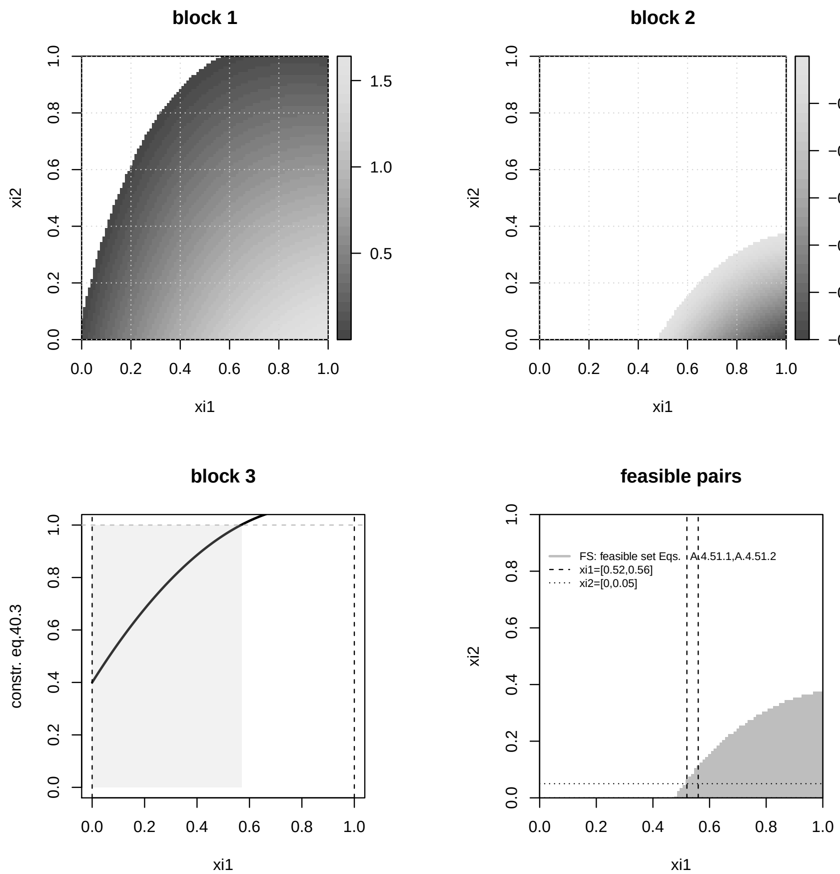

Figure 18: *Scenario 3* - Constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution when $q_t = 54$. Block 1 results from considering Eq. (A.4.51.1), block 2 results from considering Eq. (A.4.51.2) and block 3 results from considering Eq. (A.4.51.3). Block 4 shows the pairs of ξ_1 and ξ_2 associated with the optimal solution.

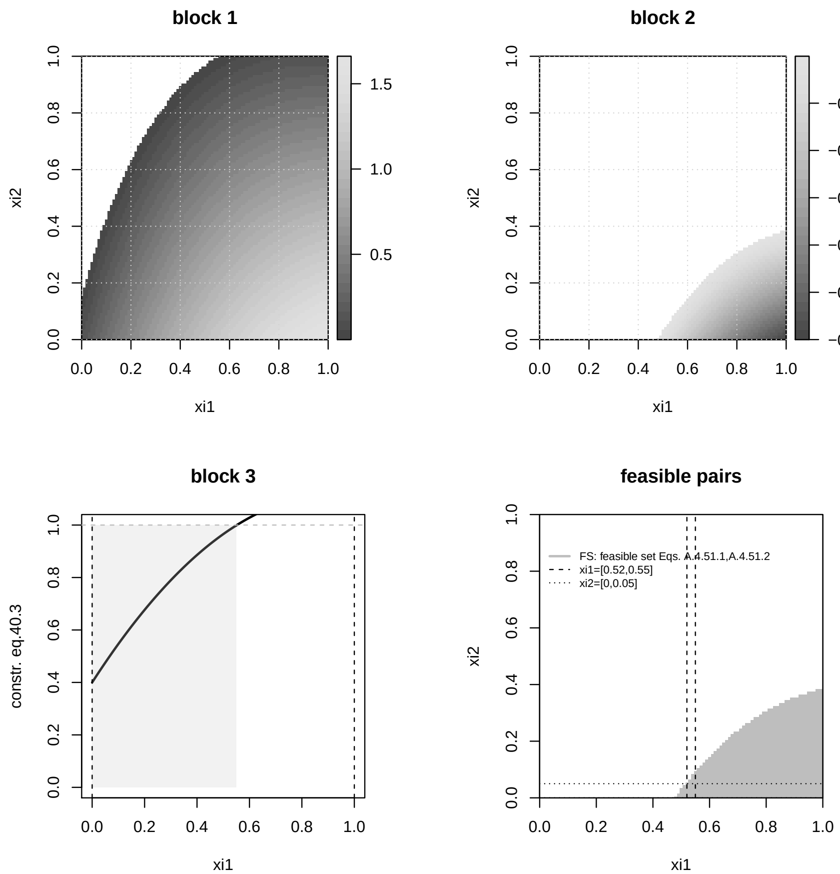

Figure 19: *Scenario 3* - Constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution when $\sigma = 0.25$. Block 1 results from considering Eq. (A.4.51.1), block 2 results from considering Eq. (A.4.51.2) and block 3 results from considering Eq. (A.4.51.3). Block 4 shows the pairs of ξ_1 and ξ_2 associated with the optimal solution.

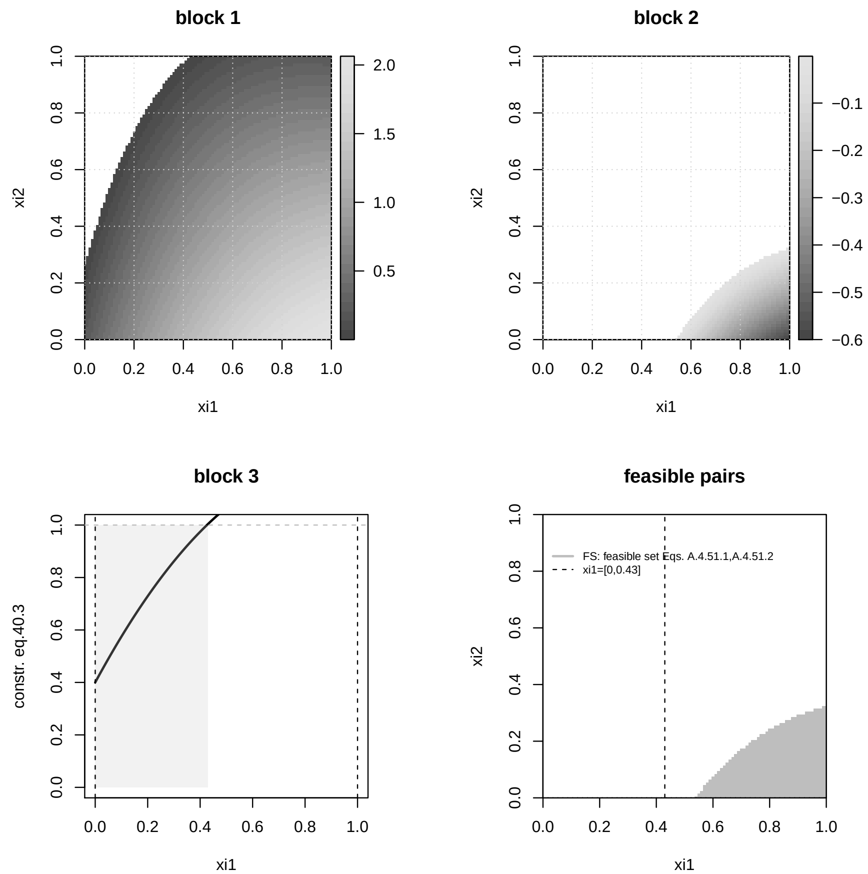

Figure 20: *Scenario 3* - Constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution when $LCOE = 70$. Block 1 results from considering Eq. (A.4.51.1), block 2 results from considering Eq. (A.4.51.2) and block 3 results from considering Eq. (A.4.51.3). Block 4 shows the pairs of ξ_1 and ξ_2 associated with the optimal solution.

Parameters	*Benchmark*	$q_t = 54$	$\sigma = 0.25$	$LCOE = 70$
$\xi_1 \in$	$[0.51; 0.52]$	$[0.52; 0.56]$	$[0.52; 0.55]$	-
$\xi_2 \in$	$[0; 0.02]$	$[0; 0.05]$	$[0; 0.05]$	-
α_1^*	1.152	1.083	1.101	-
α_2^*	0.720	0.675	0.731	-
$\xi_1\alpha_1^*$	0.5930	0.5845	0.589	-
$\xi_2\alpha_2^*$	0.007	0.017	0.019	-
γ_1	0.007	0.016	0.011	-
γ_2	0.559	0.498	0.512	-
$\mathcal{O}\left(\alpha_1^*, \alpha_2^*\right)$	3012	2808	2811	-

Table 7: *Scenario 3* - Benchmark results and comparative statics

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