Energy exchange among heterogeneous prosumers under price uncertainty

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Abstract

In this paper, we provide a real options model framing prosumers' investment in photovoltaic plants. This is presented in a Smart Grid context where the exchange of energy among prosumers is possible. We determine the optimal size of the photovoltaic installations based on the influence the self-consumption profiles on the exchange of energy among prosumers. We calibrate the model using figures relative to the Northern Italy energy market and investigate the investment decision allowing for different prosumer profiles and consider several combinations of their individual energy demand and supply. Our findings show that the shape of individual energy demand and supply curves is crucial to the exchange of energy among prosumers, and that there could be circumstances under which no exchange occurs.

Keywords: Smart Grids, Renewable Energy Sources, Real Options, Prosumer, Peer to Peer Energy Trading.
JEL Classification: Q42, C61, D81

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1 Introduction

The last decade has witnessed the increasing use of renewable energy sources as alternative to fossil fuels. Policymakers have widely encouraged such processes to achieve decarbonization targets. In this context, even though much effort is still required to achieve a sustainable energy production, a number of distributed power plants have been installed in Italy and in other EU countries. [1]

Compared to fossil fuels, renewable energy sources are known to be beneficial, but in load curves comparisons are often characterized by inflexible production which makes management of the electricity grid challenging (for instance, in terms of inefficiency, congestion rents, power outages, etc). In particular, photovoltaic (PV) production shows a certain variability depending on daily and seasonal solar irradiation, which constraints i) covering night-time demand and ii) handling peak demand since energy production is concentrated only in certain daily time slots. Therefore, innovation in the energy system should see it benefit from the introduction of digitalization in the development of so-called smart grids (SG)[2] 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 exemplified by three fundamental elements: i) the continuous integration of Distributed Energy Resources (DER), (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); and iii) the central role of 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 energy market players to adopt new behaviors. This is particularly relevant to traditional consumers who, characteristically passive in buying and receiving energy from the centralized grid, gain the opportunity to proactively manage 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

[1]The International Renewable Energy Agency (IRENA) remarks, in its *Roadmap to 2050*, on the importance of boosting investments in clean energy technologies given energy production and use still account for two-thirds of global greenhouse gas emissions.

[2]Campagna et al. (2020) describe the idea of 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) note 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) detail the evolving energy landscape from conventional electricity systems to low-carbon smart grids, highlighting the transition of distribution networks from passive structures to active systems and the emergence of end-users, who "will become active participants in system and market operation", as well as the "opening up opportunities for aggregating and coordinating consumers and system needs".

[3]As defined by the European Union. *Source* `https://ec.europa.eu/energy/en/topics/market-and-consumers/smart-grids-and-meters`

[4]systems of rooftop solar panels, storage and control devices.

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

integrating effectively and efficiently into the electricity markets (Parag and Sovacool (2016)).[6]
Indeed, the EU's *Clean energy for all Europeans package* [7] establishes a new legal framework for the internal energy market and devotes particular attention to the potential economics and environmental benefits for consumers. The EU Directive 2018/2001[8] formally introduces the *renewables consumers* and sets out the elements necessary to ensure the promotion and widespread uptake of this status.
As is widely acknowledged by researchers in this field, SG deployment, as well as its development, is also strictly related to the peer-to-peer (P2P) energy trading concept.[9]
Exchange 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]
Households and firms, as well as public authorities, can partecipate directly in the energy transition by co-investing in, producing, selling and distributing renewable energy. For these new players, the benefits arising in the energy markets range from their positive contribution in helping utilities to solve energy management issues (Zafar et al. (2018)) as well to boosting investments in renewable energy plants, thanks to the potential savings gained from cooperative investment decisions and the new flexibility in energy sourcing options. It is nonetheless important to note that these positive impacts strictly depend on the costs of adopting the technology and the shape of the demand curve of the agents involved.
The effects of direct exchange of energy among prosumers on SG deployment, have been analyzed and developed by researchers offering different perspectives

[6]SG allow instantaneous interactions between agents and the grid. Depending on its needs, the grid can send signals (prices) to the agents, and agents can respond to those signals and obtain corresponding monetary gains. These two characteristics (self-consumption and possible return energy exchange with the national grid) can add flexibility that, in turn, increases the value of the investment (Bertolini et al. (2018), Castellini et al. (2021)).

[7]The EU's *Clean energy for all Europeans package* sets the new energy union strategy with eight legislative acts, whose main pillars are: energy performance in buildings, renewable energy, energy efficiency, governance regulation, electricity market design. The recasting 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 defines new common rules for the internal market for electricity, in which the "consumer is put at the center of the clean energy transition" and new rules are defined with the aim of enabling 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)).

and exploiting various approaches.[11] A wide strand of this literature focuses on the study of the *microgrids,* as communities of prosumers, paying particular attention to their relationship with the electricity network, as well as to the behavioral characteristics of prosumers. Researchers have also recognized the significant need for 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)), with most focusing on cost minimization (Liu et al., 2018). Alternative approaches are provided instead by Gonzalez-Romera et al. (2019), in which the benefit to prosumers is determined by minimizing the exchange of energy, rather than its cost and by Ghosh et al. (2018), where the price of P2P exchanged energy is defined with the aim of minimizing the consumption of conventional energy, notwithstanding the prosumers' aim is of minimizing their own payoffs.
Yet, there remain still several interesting themes related to this topic that require further development, such as whether the additional flexibility provided by exchange P2P has value, how it might affect investment decisions, and whether it can be supported by data. Some of the literature has attemped to answer these questions by studying the possible combinations of agents in a microgird context (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 from the perspective of cost competitiveness and self-consumption maximization whereas Jiménez-Castillo et al. (2019) exploit the net present value (NPV) technique with a similar purpose but also focus on economic profitability. To the best of our knowledge, problems entailed in the possibility of matching load and supply curves in an uncertain environment, as well as in an exchange P2P framework, are yet to be investigated under this perspective.

[11] Comprehensive review is provided by Hernández-Callejo (2019)

This paper contributes to the real options literature studying investment in infrastructure for the production and exchange of energy.[12]
Among contributions to these field, those closest to ours are: Bertolini et al. (2018) and Castellini et al. (2021),on the optimal plant sizing and investment decisions under uncertainty; Luo et al. (2014), focusing 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), which develops a minimization problem with the aim of minimizing the energy exchange in a framework of two prosumer households; and Bellekom et al. (2016), whose agent-based model was developed in a residential community context under different prosumption scenarios.
Our paper provides a theoretical framework for modeling the decision of two agents[13] to invest in a 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 energy, self-consume it, and close any gap between their production and consumption needs by trading with both the national grid (N) and the other agent. Thanks to the technical structure of the SG, they can also sell energy directly to the energy market for a stochastic price.[14] Finally, each agent can buy energy from an energy provider that operates on the national energy market under a long-term contract at a fixed constant 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 the energy market. The investment decision is irreversible and taken cooperatively to allow prosumers to exchange energy P2P. Due to the high uncertainty over demand evolution and market prices, technological advances, and ever-changing regulatory environment (Schachter and Mancarella (2015); Schachter and Mancarella (2016); Cambini et al. (2016)), we build a real options (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 the characteristics of their supply-demand profiles that favor the exchange of energy and whether they are compatible with the existence of an exchange P2P framework. Secondly, we identify the size of the PV plant that maximizes the joint benefit

[12] 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, focus 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). With respect to the real options literature, we complement studies pertaining to the energy sector, which include 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).

[13] Such agents are intended as two small households willing to become prosumers.

[14] Note that, for the sake of simplicity, we calibrate the model using the day-ahead energy prices for Northern Italy.

of the two agents and, finally, focus on the quantity of energy exchange P2P and the self-consumption profiles which allow prosumers to attain the highest economic savings.

While the value of self-consumption and exchange (Bertolini et al. (2018); Castellini et al. (2021)) are two topics already studied in the literature, inquiry into the conditions for the initiation of an exchange P2P structure in a two-agent RO framework and the calculation of exchange energy rates is, to the best of our knowledge, novel.

To address this, we study the investment decision under different prosumers' behaviors, taking into account all possible combinations of energy demand and supply for the two agents in exchange P2P. These are summarized in four scenarios we consider. Scenario 1 refers to the case of an excess of supply from both prosumers. Scenario 2 conversely focuses on an excess of demand. Scenario 3 describes the case where prosumer 1 needs no more than the amount the prosumer 2 could provide, while prosumer 2 needs more than what prosumer 1 can provide. Scenario 4 instead analyzes the case whereby prosumer 2 needs no more than what prosumer 1 could provide, while prosumer 1 needs more than the amount prosumer 2 can provide. Each scenario is therefore characterized by constraints in terms of energy exchange between the prosumers, leading to specific conditions with which the prosumers' self-consumption behaviors must comply to assure the feasibility of the scenario. 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 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 the other parameters refer to data provided by EUROSTAT, the International Renewable Energy Agency (IRENA) and International Energy Agency (IEA).

The main findings of our paper are here briefly listed.

- All four scenarios show some feasible conditions for energy exchange and only a few have economic significance and are feasible in reality.
- Among these, the profiles assuring 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 excess supply (as in the case of scenario 1) they also sell some of their production to N in order to maximize the benefit. If they have excess demand (as in the case of scenario 2), they sell nothing to N but cover all their daytime demand with their own energy production.
- The scenarios showing the lowest savings are the two asymmetric scenarios (3 and 4) characterized by excess demand for one agent and excess supply for the other, and viceversa. The combination which guarantees the existence of the exchange P2P framework is that whereby one agent produces to self-consume and sell, and the other agent buys the surplus of

the other agent and sells all of its production to the grid. The maximum savings are guaranteed by the two agents cooperating in such a way that one of them allows the other to maximize their own earnings. Under a cooperative perspective, the gain is shared between the agents. In this context, it is observed that one agent invests in an over-sized PV plant, while the other chooses a plant size similar to those identified in scenarios 1 and 2.

- In all scenarios, although the prosumers are characterized by different supply-demand profiles, very similar total savings are achieved. This depends on the possible combinations of production, self-consumption and energy exchange. In some cases, this involves making the most of mutual exchange, in other cases producing and exchanging with N, so as to reduce energy costs. The best case (i.e. having the highest NPV), however, is that where the prosumers are characterized by excess supply and asymmetric and complementary load curves.

By comparing of the feasible solutions and the daily 24-hour load curves we are able to identify, for each scenario, the optimal combinations to maximize prosumers' savings.
The paper now proceeds as follows: in Section 2, we present the basic set-up of our model. In Section 3, we identify the expected net energy cost to be borne by each prosumer once the PV project is activated. In Section 4, we set the optimization problem aiming to identify the optimal capacities of the prosumers' PV system and describe our four exchange P2P scenarios. For each of the latter, we find analytically the respective prosumers' optimal capacities (detailed in Appendix A.4). In Section 5, we present the model calibration. Section 6 presents and discuss our main results. Section 8 concludes.

2 The basic set-up

Consider two households ($i = 1, 2$) who currently purchase energy from a national provider at a constant unit energy price $p > 0$, on the basis of a long-term contract.
The two agents contemplates the opportunity of setting up an exchange P2P framework, where they would act as *prosumers*. To do so, they must cooperatively invest in a project for the installation of i) two individual PV systems and ii) an SG, allowing them to exchange energy with each other, i.e. energy exchange P2P, and with the national energy market. For brevity, we will define the purchase of energy from the energy provider as "purchase of energy from N" and the sale of energy on the energy market as "sale of energy to N".
To set up our model, we introduce the following assumptions: [15]

[15] Note that, in terms of model set-up, some of our assumptions are shared with Castellini et al. (2021), such as our assumptions 7, 8, 9.

Assumption 1 ***(project time horizon)***. *The investment project, once undertaken, lasts forever.* [16]

Assumption 2 ***(individual energy demand).*** *The energy demand of each prosumer i is constant overtime, normalized to 1 and it is covered as follows:* [17]*:*

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

where

- α_i represents the average energy produced per unit of time, given a certain power capacity [18] of the PV system, installed by each prosumer i (henceforth, the PV plant size). 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 intended forself-consumption.[19]
- 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 at price p, where $\bar{b}$ is the night-time individual energy demand that must necessarily be covered by purchasing energy from N. Note that, in general, its magnitude may depend on the prosumer's daily load patterns, and may be lowered by installing a PV system (Luthander et al., 2015).

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

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

[16]The project is assumed to last for a long period of time that, without loss of generality, can be approximated to infinity.

[17]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 $s \in [0, 24]$.

[18]α_i accounts for the potential production losses due to variation in temperature, low irradiance, shading and albedo (Bertolini et al., 2018).

[19]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.

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.* [20] *We assume that the selling price q_t is stochastic and evolves overtime according to the following Geometric Brownian Motion (GBM):*[21]

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

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 $\ln q + \left(\theta - \frac{\sigma^2}{2}\right) t$ 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 the market selling price at the beginning of each time period t. For simplicity, we assume that they can only trade energy on the energy market at this specific time point.*

By Assumption 4, once informed of the selling price, 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 exchange P2P.

Assumption 5 ***(exchange P2P price).*** *The prosumers agree to exchange energy at the price v_t, which is defined as follows:*

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

where, as shown in Appendix A.1, by m and $1 - m$, with $m \in (0, 1)$, we denote the seller's and buyer's strengths exerted in the price bargaining.[22] Note that, when the buying price, p, is higher than the selling price q_t the exchange P2P is always more convenient than purchasing from/selling energy to N since $v_t < p$ and $q_t < v_t$, respectively.

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

[21]The GBM is largely used in the field of real options and renewable energy (Kozlova (2017) for a review of the literature). Specific discussion regarding its use in energy prices' dynamic approximation is found in Borovkova and Schmeck (2017) and Andreis et al. (2020).

[22]Zafar et al. (2018) state that the negotiation of the energy price's 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:* [23]

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

where $K_A > 0$ represents the cost to be undertaken in installing 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.[24]

Assumption 7 ***(the cost of solar energy).*** *The unit cost of producing solar energy is nil.*[25]

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 $r > \theta$.* [26]

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, offering 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 progress, storage technologies are still far from being cost effective.[27]

[23]We consider a quadratic function for the sake of simplicity. None of our results would be affected were 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 $\delta > 1$ be assumed.

[24]As the number of households involved in the PV investment project increase, each household may benefit from economies of scale relating to the fixed cost component K_A.

[25]Since solar radiation represents the production input and is free, the marginal production costs for the PV power plants may be considered negligible (Bertolini et al., 2018, Tveten et al., 2013, Mercure and Salas, 2012).

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

[27]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 required to fully characterize the exchange P2P:

i) No prosumer can 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 they actually need,that is:[28]

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

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):*

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

As to the amount of energy produced by their own PV system, note that 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:[29]

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

The solution of Problem (10) is:

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

[28]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.

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

since:

$$
\begin{array}{lll}
c_i^{NSCE}(q_t;\alpha_i) < c_i^{SCE}(q_t;\alpha_i,\gamma_i,\gamma_j) & \text{for} & q_t > p \\
c_i^{NSCE}(q_t;\alpha_i) \geq c_i^{SCE}(q_t;\alpha_i,\gamma_i,\gamma_j) & \text{for} & q_t \leq p
\end{array}
$$

Let's now first consider the range of values $q_t > p$ and denote by $C_i^{NSCE}(q_t;\alpha_i)$ 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, $C_i^{NSCE}(q;\alpha_i)$ solves the following Bellman equation:

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

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), $C_i^{NSCE}(q;\alpha_i)$ can be determined by solving the following differential equation:

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

where $\Gamma = -r + \theta q \frac{\partial}{\partial q_t} + \frac{1}{2}\sigma^2 q_t^2 \frac{\partial^2}{\partial q_t^2}$ is a differential operator.
Let's now turn to the range of values $q_t < p$ and denote by $C_i^{SCE}(q_t;\alpha_i,\gamma_i,\gamma_j)$, 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, $C_i^{NSCE}(q;\alpha_i)$ is the solution of the following Bellman equation:

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

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), $C_i^{NSCE}(q;\alpha_i)$ can be determined by solving the following differential equation:

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

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

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

and

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

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 their PV system to N. This is, of course, the case when $q_t > p$. Further, note that, if the size installed is sufficiently large, 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 $S_i\left(q_t;\alpha_i,\gamma_i,\gamma_j\right)(\frac{p}{r} - \frac{q_t}{r-\theta})$ 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 Conditions (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 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 simplicity, a scenario where self-consumption and exchange P2P would be, once the investment is activated, immediately convenient, i.e. when $q_t < p$.
A necessary condition for investing in the project is that a benefit arises from it with respect to the status quo scenario, that is, not self-producing one's own energy and covering one's 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 NPV of the PV project is maximized. Formally:

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

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 *P2P exchange scenarios*. Each of these 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 solutions of Problem (19), distinguishing the internal solutions and the corner solutions. It must, however, be stressed that the mathematical solutions do not always reflect 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 discuss the real feasibility of the scenarios

according to the outcomes obtained from the calibration of the model and in line with the results found in Appendix A.4.

Scenario 1: excess supply in the energy exchange P2P. In Scenario 1 we focus on the case of excess supply from both prosumers in exchange P2P and the constraint presented in Eq. (6) is detailed as follows[30]:

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

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

In the mid of both Inequalities (21) and (22), we find the quantity of energy each prosumer demands from 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 [31] and ii) consumed their 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 can be immediately seen, under this scenario, the exchange P2P 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 the other prosumer could actually provide.

Scenario 2: excess demand in the energy exchange P2P. 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 demands from the other prosumer, i.e. $(1 - \bar{b}) - \xi_i\alpha_i$, is higher than the quantity of energy that each prosumer can actually supply, i.e. $(1 - \xi_j)\alpha_j$. This implies that the exchange P2P 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.

Scenario 3: non complementarity in the energy exchange P2P. Under Scenario 3, prosumer 1 demands less energy than the quantity that prosumer 2 could provide, while prosumer 2 may need i) more energy than the quantity that prosumer 1 can provide or ii) exactly the quantity that prosumer 1 could provide. The constraints characterizing this scenario are the following:

[30] Eq. (21) refers to prosumer 1 and (22) to prosumer 2. The same format applies in the successive scenarios.

[31] 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.

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

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

Scenario 4: non complementarity in the energy exchange P2P. Scenario 4 is symmetric to scenario 3. In fact, in this case, prosumer 2 demands less energy than the amount that prosumer 1 could provide, while prosumer 1 may need i) more energy than the quantity that prosumer 2 can provide or ii) the exact quantity that prosumer 2 could provide.

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

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

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 the Northern Italy from 2012 to 2018.[32] The price q_t refers to Northern Italy region and reference time interval is set at 2012-2018. We take into account only the prices corresponding to the hours of the PV plant's operation, that is, from 8 a.m. to 7 p.m.. Average quarterly prices are then computed and seasonally adjusted.
We use the *Shapiro Test* [33] and the *Augmented Dickey-Fuller Test* (ADF) [34] to test whether the price q_t follows a GBM with drift, i.e. non stationarity.
The drift rate, θ, and the volatility rate, σ, of the process of 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.[35]
The value of the price q_t for both prosumers is 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 N (p) is set equal to 154.00 euro/Mwh, which is the average value of the electricity price paid by Italian

[32] The Spot Electricity Market (MPE) is part of the Italian wholesale electricity market, or IPEX (Italian Power Exchange). It consists of the Day-ahead Market (MGP), the Intra-day Market (MA or MI) and the Anchillary Services Market (MSD). The MGP is a single implicit auction market where zonal market clearing prices are determined. A detailed discussion of the zonal market framework is provided by Gianfreda and Grossi (2012). Data are sourced from the website of the Italian System Operator *Gestore Mercati Energetici* (GME).

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

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

[35] The estimates were computed on the basis of quarterly average prices and converted to annual terms.

household consumers over the reference time interval according Eurostat.[36] 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's energy output is the product of the size (kWp) and the local solar insolation that takes the size 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 constructing a cost function in terms of kWh/year instead of kWp.
The assumed average plant life time, T, is set equal to 25 years.[37] The levelized cost of energy (LCOE) for the PV technology is set equal to 80 euro/MWh.[38] The parameter K_A represents the cost the prosumers pay to be connected to the SG and we set it equal to $0.15K_B$.[39]
Table 1 summarizes all the parameters used in the model's calibration.

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

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

[38]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.

[39]With reference to Italy, we set parameter K_A on the basis of the fees for 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, GME website
σ	volatility	0.32	Calibrated on Northern Italy zonal prices, GME website
q	average level of the price q_t over the considered time period	58.85	Northern Italy zonal prices, GME website
p	energy purchase price	154.00	Eurostat, Energy Statistics, Electricity prices for household consumers.
$\bar{b}$	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	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,[40] our aims are as follows: i) to investigate the role of self-consumption as a driver for setting up the exchange P2P (ξ_1, ξ_2), ii) to determine the optimal size of the individual PV system, i.e. (α_1^*, α_2^*), and iii) to determine the expected NPV of the PV project, i.e. $(O(\alpha_1^*, \alpha_2^*))$.

The solutions of Problem (19) lead to several feasible outcomes. Some of them, however, even if mathematically sound, are not realistic. This is, for instance, the case for outcomes 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 depends on the structure of the model such that the entire day is com-

[40]The findings provided relate to Scenarios 1, 2 and 3 only. Scenario 4 is excluded since findings would be symmetric with respect to those obtained in Scenario 3.

pressed into a unique point in time. In reality the day is divided into 24 hours and demand and supply are time dependent. Therefore, there exist some solutions in wherein their matching does not occur in a 24-hour framework.
In the light of these remarks, in Table 2, we show the outcomes that are, in our view, the most representative of our four scenarios. Our selection is based on the following requirements: 1. the outcomes are all mathematically feasible, as we show in Appendix A.4; 2. we identify those outcomes that are consistent with realistic daily supply and demand curves; 3. we focus on those outcomes characterized by the highest NPV. Interestingly, the outcomes we show have similar NPVs despite presenting very different supply and demand functions.
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, examining their characteristics to understand which case is best and the key elements that make it more favourable 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 characterized by the highest NPV and in Figure 1 we show a realistic combination of supply and demand that can support it.

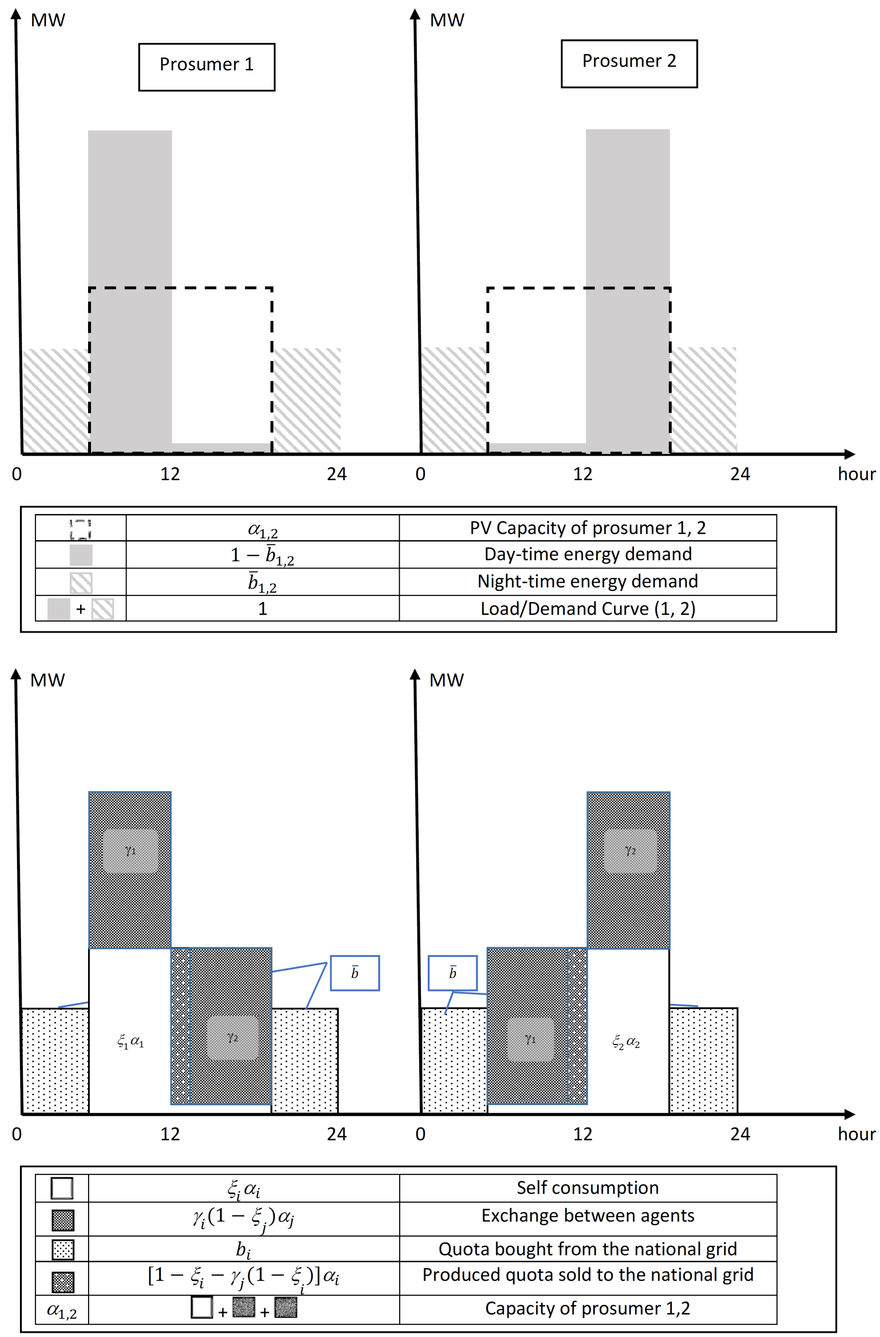

Figure 1: *Scenario 1* - Load and supply curves and distribution of energy trade and consumption.

In greater detail, at the top of Figure 1 we find, for each agent, the daily load curves over 24 hours and the quantities of energy produced by each prosumer's PV system. The dashed areas correspond to the night demand, while the gray areas correspond to the day demand. The dashed frame represents the size 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 sale to N. In the following, we show how the individual demand is covered through self-consumption, energy exchange with the other prosumer, and purchases from N. The dark gray areas represent the energy exchange between the two agents, i.e. γ_1 and γ_2.

From Table 2, we can observe that the two prosumers in scenario 1 have an energy 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, manage to have an optimal symmetrical plant size (0.710) that of the PV plant's operation 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 N and, at the same time, each is able to sell 0.110 to it. 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 that of scenario 3. We notice also that these two scenarios are very similar in terms of demand and supply composition. It can be seen that, 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 showing 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 Figure 2 shows.

Compared to scenario 1, the two prosumers do not sell any energy to N and in this situation, the PV plant size is set for maximum daytime consumption. In this way, the two agents can minimize their costs, but do not gain an extra profit by selling excess energy production to N, as is the case in scenario 1. See, for example, in the following figure 3, the results of the corner solution 1 of scenario 2.[41] The two PV plants' 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 N an amount of 0.177, which is 18% of the total demand of one agent. This combination leads to a lower $\mathcal{O}(\alpha_1^*, \alpha_2^*)$ which is equal to 2823.

[41] See the second column of Table 6 in the Appendix A.5.

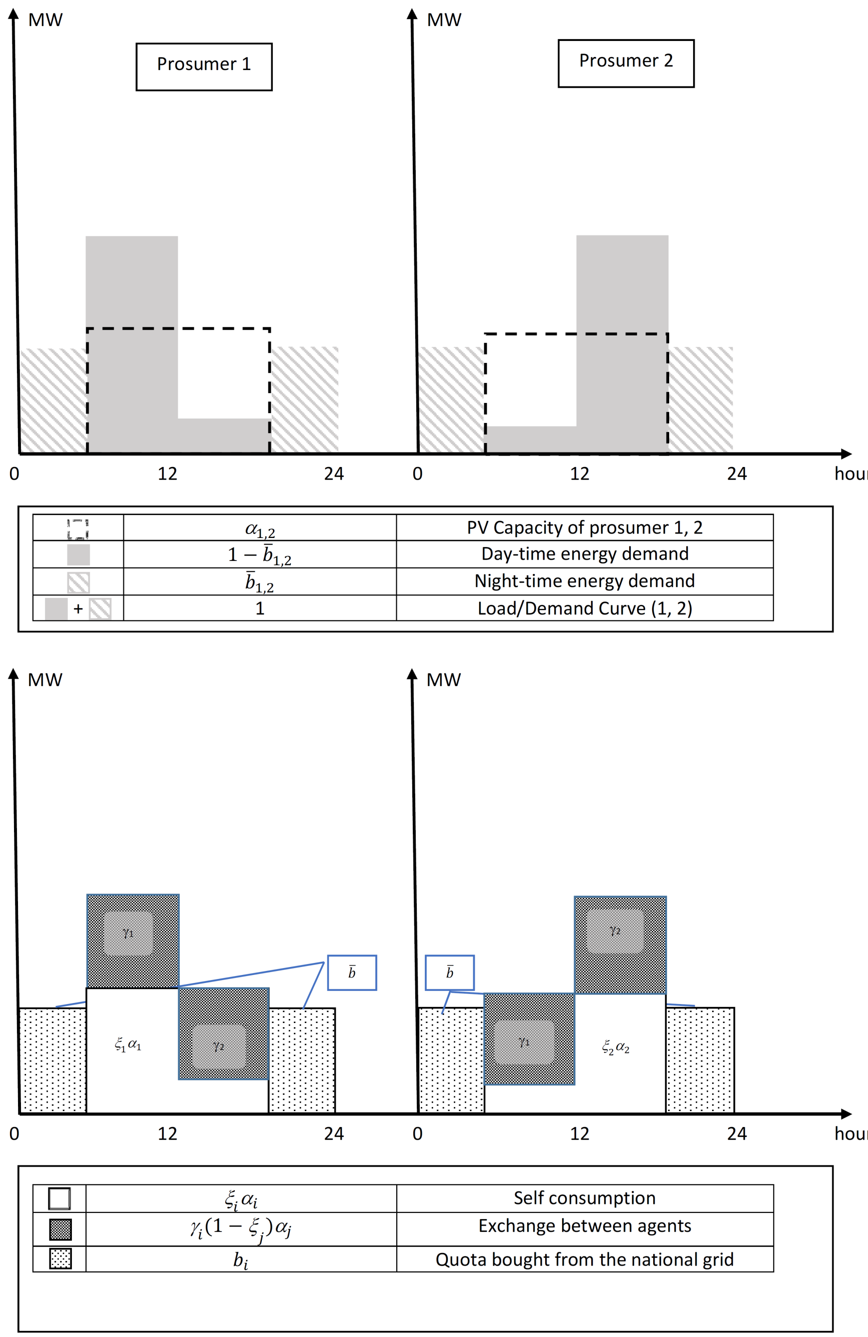

Figure 2: *Scenario 2, Corner Solution 3* - Load and supply curves and distribution of energy trade and consumption.

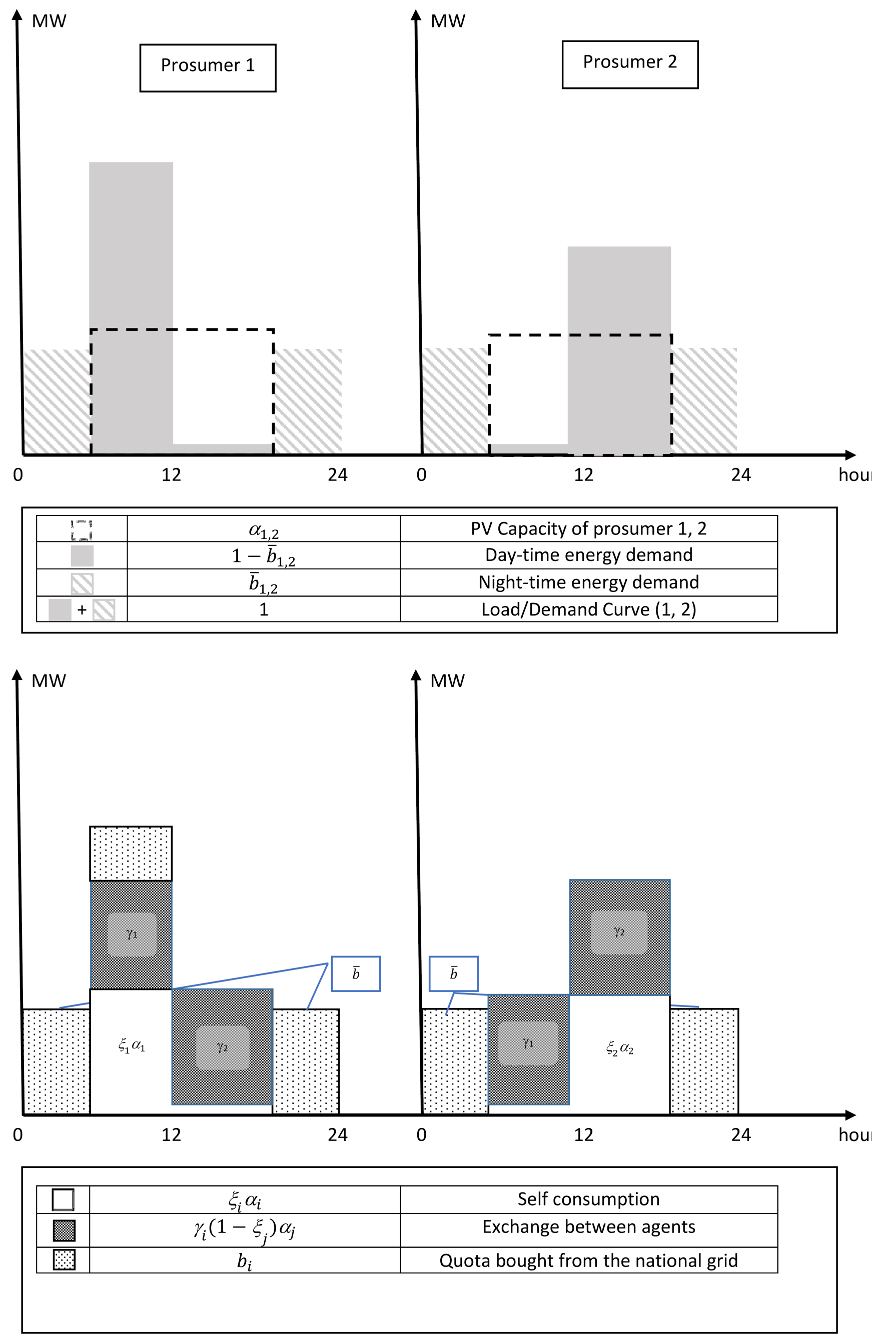

Figure 3: *Scenario 2* - Load and supply curves and distribution of energy trade and consumption.

About scenario 2, we can conclude that the best outcomes are feasible only if the self-consumption levels (ξ_1 and ξ_2) are quite high, specifically, higher than 0.50. This requires a relatively small PV system size (i.e 0.60). Otherwise, the agents would have too much energy to sell to N and this would be sub-optimal. This allows a proportionally high level of self-consumption, as the results show. Taken all together, these features justify the lower NPV.
Scenario 3 presents the non complementarity case. The solution is asymmetric, because in this context prosumer 1 needs in exchange no more energy than the other prosumer could provide, while prosumer 2 needs more than what prosumer 1 can provide. The results in the last column of Table 2, show that agent 1 installs a PV size larger than the demand, i.e. 1.152, while prosumer 2 installs a PV plant of a size very similar to scenario 1's, i.e. 0.720. The interesting result is that, despite having a quite different supply-demand structure, the levels generated are not very far from those obtained in scenario 2. In fact, we get an $\mathcal{O}\left(\alpha_1^*, \alpha_2^*\right)$ equal to 3012. Let's present the main insight behind this outcome.
The interesting result is that prosumer 1 self-consumes a little more than half of its production (0.593), while the balance 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 N; thus its self-consumption is almost nil. In this arrangement, the two prosumers manage to maximize their joint pay-offs, even though their situation is characterized by supply-demand asymmetry. Prosumer 2 sells to N 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 the agents' overall total value. The net effect is an NPV equal to 3012, close to the other scenarios.
In this scenario, the prosumers exploit their own asymmetry by transforming one agent into a pure link between production and sale and playing on the price differential. This results can only be achieved with perfect coordination between prosumers.
It is interesting at this point to consider whether it is worth building up the exchange P2P in this scenario. Let us now summarize our results by reflecting on the conditions under which the P2P exchange is particularly profitable. First of all, we early acknowledged that not all the results that are feasible, and which we report in the related appendices, 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) the exchange P2P can exist only if the prosumers are almost perfectly asymmetrical and have self-consumption levels of about 40-50% of the PV production (70% for scenario 2) and the same day/night distribution. Therefore the exchange P2P makes sense only under certain conditions and with particular combinations of supply and demand. It could also be relevant in a context similar to scenario 3, where an asymmetrical structural situation exists and the two agents try to maximize the joint value of the PV project.

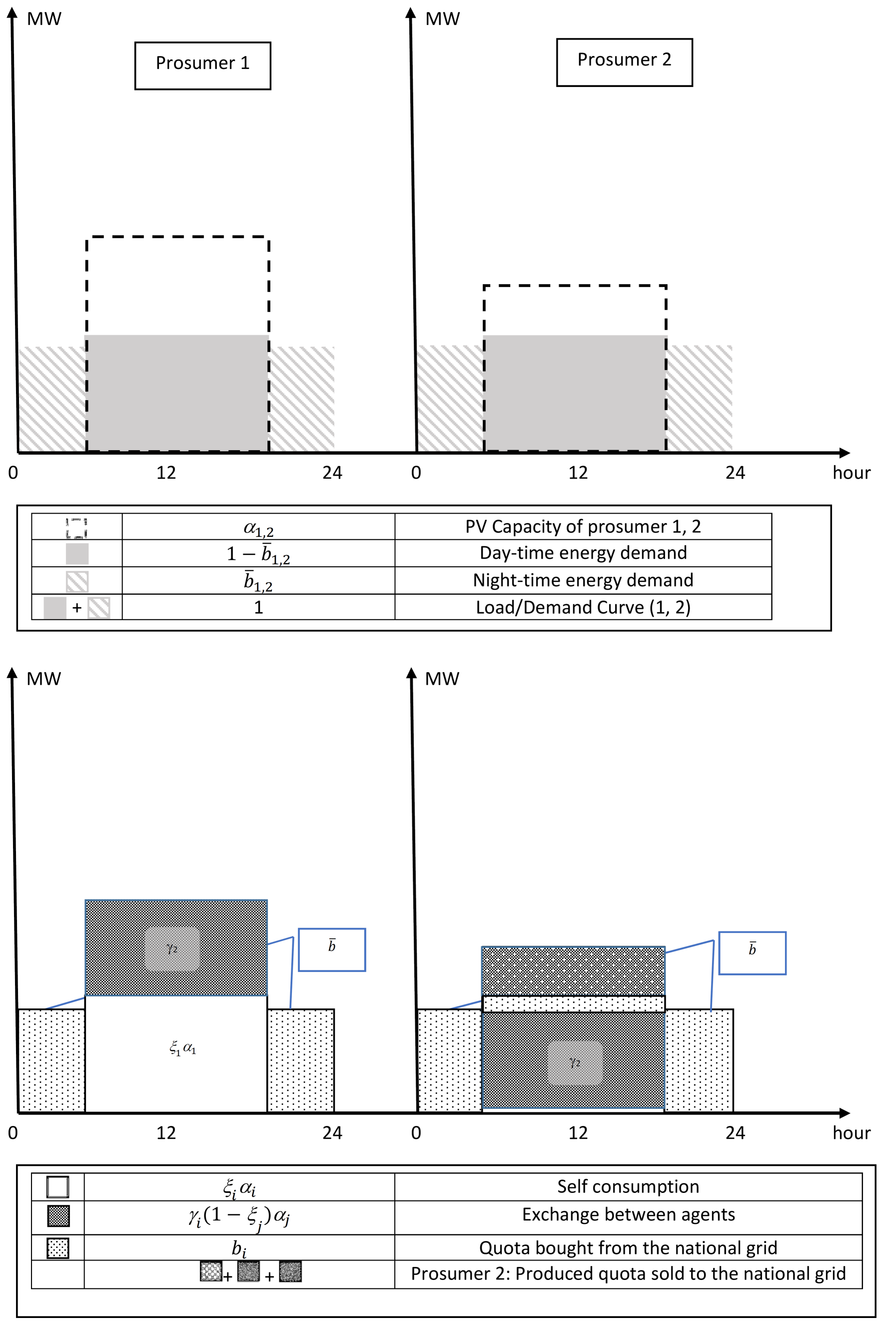

Figure 4: *Scenario 3* - Load and supply curves and distribution of energy trade and consumption.

7 Conclusions

In this work, we have modeled the investment decision of two prosumers in a PV system in a SG framework. Each prosumer can: (i) self-consume their 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 N, which is assumed to be stochastic. We investigate the cooperative investment decision under different prosumer behaviors in exchange P2P, considering all the possible combinations of energy demand and supply available to the two prosumers. These are summarized in four different exchange scenarios.

Our findings show that it is not in all the cases convenient to develop an exchange P2P framework. Indeed, after calibrating our model to the Northern Italy energy market, we analyzed checked the feasibility of the PV investment under the four different scenarios. Among all feasibility 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 identified the supply and demand profiles of prosumers for which it makes sense to build an exchange P2P structure. The best case occurs when the two prosumers have excess demand in the P2P exchange, and their profiles exhibit by perfectly asymmetric and complementary supply and load curves. In this case, where the two prosumers build two symmetrical PV plants of a smaller size relative to their demand, a share of the energy production is self-consumed; a share is exchanged P2P with the aim of matching the hourly consumption demand reciprocally; and a share is sold to N. Nothing is bought in daytime consumption from N.

A second feasible scenario refers to the case where the two prosumers are characterized by excess demand. Both produce and consume from a smaller plant, relative to the previous one, that is set at the daytime demand level. Nothing is sold to or purchased from the national grid in the daytime. The exchange P2P is also convenient, with asymmetry between the two agents. Indeed, if one prosumer has excess demand and the other excess supply, our model finds a positive NPV when an agent produces to self-consume and sell, and the second agent buys the surplus of the other and sells all of its own production to N. The maximum savings are guaranteed by the two agents' cooperating in investment decisions such 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 build an oversized his PV plant, while the other builds one of a size smaller than his demand. Therefore, the exchange P2P framework makes sense only under certain conditions and with particular combinations of supply and demand, although we found that the exchange P2P could have a closer NPV while showing different and opposite supply and demand profiles. Much depends on the level of self-consumption, the size of the PV system and the degree of cooperation between agents.

To conclude, since it is widely recognized that policymakers support the deployment of the exchange P2P due to its promise in terms of i) its positive contribution to decarbonization goals, ii) the potential for improved management of the electricity network, and iii) actively involving of the prosumers in the energy market, on the basis of our findings it is important to remark that further research on the conditions assuring the optimal set-up of the exchange P2P must be developed. Aspects including uncertainty, demand and supply matching in exchange, and optimal PV plant sizing need to be investigated intentionally to support policymakers in their future task of establishing an enabling regulatory framework for the energy transition path. Lastly, possible extensions of our research could focus on examining, on one side, some specific aspects of the exchange P2P in depth, and on the other, the application of our framework in the renewable energy communities (REC) context. Extending research on the study of the main drivers of uncertainty in the exchange P2P structure and, specifically, the introduction of a stochastic energy purchase price could provide further insights into the optimal energy production framework set up. In a REC context, our model should be extended in order to allow for the options to enter, exit and re-enter the community whenever convenient. Such a model would be useful for clarifying the policy implications of regulatory and contractual frameworks for initiating and sustaining REC.

A Appendix

A.1 Nash price bargaining

Let's consider the bargaining process leading up 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 is 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:

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

where by m and $1 - m$ with $m \in (0, 1)$ we denote the seller's and buyer's strengths exerted in the bargaining.
The first-order Condition for the maximization problem (A.1.1) is: [42]

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

Solving Eq. (A.1.2) we obtain

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

[42]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):[43]

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

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 $\widehat{Y}_i^{SCE} q_t^{\beta_1}$ represent 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

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

smooth-pasting Condition

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

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.

[43] 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 the following shows, is always the case:

$$\begin{aligned}\left.\frac{dH\left(q_t\right)}{dq_t}\right|_{q_t=0} &= -\frac{1}{r-\theta}<0\\ \left.\frac{dH\left(q_t\right)}{dq_t}\right|_{q_t=p} &= \frac{\beta_2}{r-\theta}\frac{r-\beta_1\theta}{r(\beta_1-\beta_2)}<0\end{aligned}$$

A.4 The energy exchange P2P scenarios

A.4.1 Scenario 1: excess supply in the energy exchange P2P

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 exchange P2P 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 alternative to 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 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:

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

A.4.2 Scenario 2: excess demand in the energy exchange P2P

Suppose that:

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

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

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

When $q_t < p$, since the exchange P2P is more convenient than trading energy with N, the two prosumers exchange the following quantities of energy:

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

As for the excess demand, each prosumer has no alternative to purchasing energy from N at price p.
Substituting Eqs. (A.4.12) and (A.4.13) into (20) and solving Problem (19) yields:[44]

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

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

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

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:

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

Corner solution 1. Consider the case where

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

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

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

[44] 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 it convenient to exchange the following amounts of energy:

$$\gamma_1 = (1-\xi_2)\alpha_2, \tag{A.4.21}$$
$$\gamma_2 = (1-\xi_1)\alpha_1, \tag{A.4.22}$$

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

$$\alpha_1^* = \frac{(1-\bar{b})(1-\xi_1)}{(1-\xi_1)^2+\xi_2^2} - \frac{\xi_2(1-\xi_1-\xi_2)}{(1-\xi_1)^2+\xi_2^2}\frac{\frac{p}{r} - Y^{SCE}(\frac{q_t}{p})^{\beta_1}}{K_B}, \tag{A.4.23}$$
$$\alpha_2^* = \frac{(1-\bar{b})\xi_2}{(1-\xi_1)^2+\xi_2^2} + \frac{(1-\xi_1)(1-\xi_1-\xi_2)}{(1-\xi_1)^2+\xi_2^2}\frac{\frac{p}{r} - Y^{SCE}(\frac{q_t}{p})^{\beta_1}}{K_B}. \tag{A.4.24}$$

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

$$\alpha_1^* > 0, \tag{A.4.25.1}$$
$$\alpha_2^* > 0, \tag{A.4.25.2}$$
$$\alpha_1^* + \alpha_2^* < 2(1-\bar{b}), \tag{A.4.25.3}$$

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:

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

Corner solution 2. Suppose that

$$(1-\bar{b}) - \xi_1\alpha_1 = (1-\xi_2)\alpha_2 > 0, \tag{A.4.27}$$
$$(1-\bar{b}) - \xi_2\alpha_2 > (1-\xi_1)\alpha_1 > 0. \tag{A.4.28}$$

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

$$\alpha_2 = \frac{(1-\bar{b}) - \xi_1\alpha_1}{(1-\xi_2)}, \tag{A.4.29}$$
$$\alpha_1 + \alpha_2 < 2(1-\bar{b}). \tag{A.4.30}$$

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

$$\gamma_1 = (1-\xi_2)\alpha_2, \tag{A.4.31}$$
$$\gamma_2 = (1-\xi_1)\alpha_1, \tag{A.4.32}$$

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

$$\alpha_1^* = \frac{(1-\bar{b})\xi_1}{(1-\xi_2)^2+\xi_1^2} + \frac{(1-\xi_2)(1-\xi_1-\xi_2)}{(1-\xi_2)^2+\xi_1^2}\frac{\frac{p}{r} - Y^{SCE}(\frac{q_t}{p})^{\beta_1}}{K_B}, \tag{A.4.33}$$
$$\alpha_2^* = \frac{(1-\bar{b})(1-\xi_2)}{(1-\xi_2)^2+\xi_1^2} - \frac{\xi_1(1-\xi_1-\xi_2)}{(1-\xi_2)^2+\xi_1^2}\frac{\frac{p}{r} - Y^{SCE}(\frac{q_t}{p})^{\beta_1}}{K_B}. \tag{A.4.34}$$

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

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

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:

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

Corner solution 3. Suppose that

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

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

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

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

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

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

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

A.4.3 Scenario 3: non complementarity in the energy exchange P2P

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 it convenient to exchange 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:

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

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:

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

A.4.4 Scenario 4: non complementarity in the energy exchange P2P

Suppose that:

$$\begin{aligned}(1-\bar{b})-\xi_1\alpha_1 &\geq (1-\xi_2)\alpha_2>0, && \text{(A.4.62)}\\ 0 &< (1-\bar{b})-\xi_2\alpha_2<(1-\xi_1)\alpha_1. && \text{(A.4.63)}\end{aligned}$$

Internal solution. Consider the case where:

$$\begin{aligned}(1-\bar{b})-\xi_1\alpha_1 &> (1-\xi_2)\alpha_2>0, && \text{(A.4.64)}\\ 0 &< (1-\bar{b})-\xi_2\alpha_2<(1-\xi_1)\alpha_1. && \text{(A.4.65)}\end{aligned}$$

Prosumer 1 and prosumer 2 find it convenient to exchange the following quantities of energy:

$$\begin{aligned}\gamma_1 &= (1-\xi_2)\alpha_2 && \text{(A.4.66)}\\ \gamma_2 &= (1-\bar{b})-\xi_2\alpha_2 && \text{(A.4.67)}\end{aligned}$$

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

$$\begin{aligned}\alpha_1^* &= \frac{1}{K_B}\left\{(1-\xi_1)\frac{q_t}{r-\theta}+\xi_1\left[\frac{p}{r}-Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right]\right\}>0 && \text{(A.4.68)}\\ \alpha_2^* &= \frac{1}{K_B}\left\{\xi_2\frac{q_t}{r-\theta}+(1-\xi_2)\left[\frac{p}{r}-Y^{SCE}\left(\frac{q_t}{p}\right)^{\beta_1}\right]\right\}>0 && \text{(A.4.69)}\end{aligned}$$

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

$$\begin{aligned}(1-\bar{b}) &> \xi_1\alpha_1^*+(1-\xi_2)\alpha_2^* && \text{(A.4.70.1)}\\ (1-\bar{b}) &< (1-\xi_1)\alpha_1^*+\xi_2\alpha_2^* && \text{(A.4.70.2)}\\ \xi_2\alpha_2^*+\bar{b} &< 1 && \text{(A.4.70.3)}\end{aligned}$$

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

$$\begin{aligned}(1-\bar{b})-\xi_1\alpha_1 &= (1-\xi_2)\alpha_2>0, && \text{(A.4.72)}\\ 0 &< (1-\bar{b})-\xi_2\alpha_2<(1-\xi_1)\alpha_1. && \text{(A.4.73)}\end{aligned}$$

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

$$\begin{aligned}\alpha_2 &= \frac{(1-\bar{b})-\xi_1\alpha_1}{(1-\xi_2)}, && \text{(A.4.74)}\\ \alpha_1+\alpha_2 &> 2(1-\bar{b}). && \text{(A.4.75)}\end{aligned}$$

Prosumer 1 and prosumer 2 find it convenient to exchange 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:

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

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:

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

A.5 Numerical results

A.5.1 Scenario 1: excess supply in the energy exchangeP2P.

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 NPV 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, as it is, for instance, in 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 allowable gap starts shrinking as the optimal size increases. Finally, Figure 6 shows the set of (ξ_1, ξ_2) satisfying the Constraints above when each prosumer installs a capacity, α^*, equal to 0.71.[45]

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 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,[46] $O(\alpha_1^*, \alpha_2^*)$ (See Table 3). We notice also that, with respect to the benchmark case, the prosumers' self-consumption profiles must be closer.[47] 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 a 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 allowable gap between ξ_1 and ξ_2 but their allowable 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.

[45] 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 are 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).

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

[47] As Figure 5also makes immediately clear.

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.

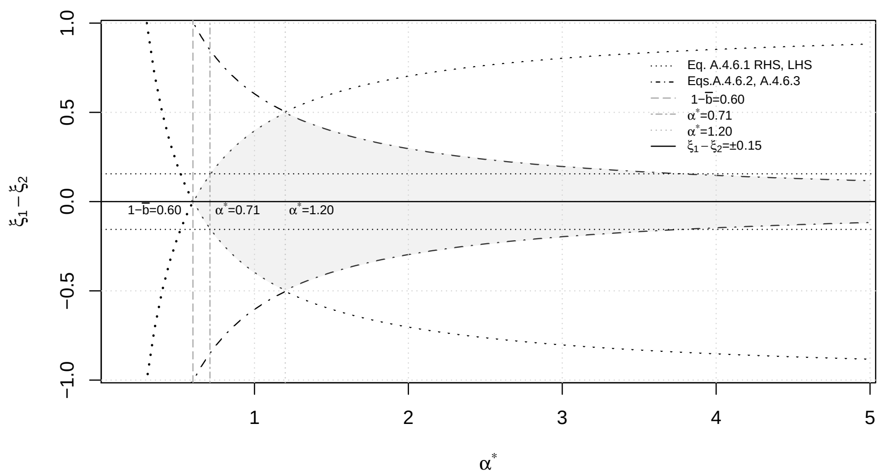

Figure 5: *Scenario 1* - The set of (ξ_1, ξ_2) associated with a feasible solution.

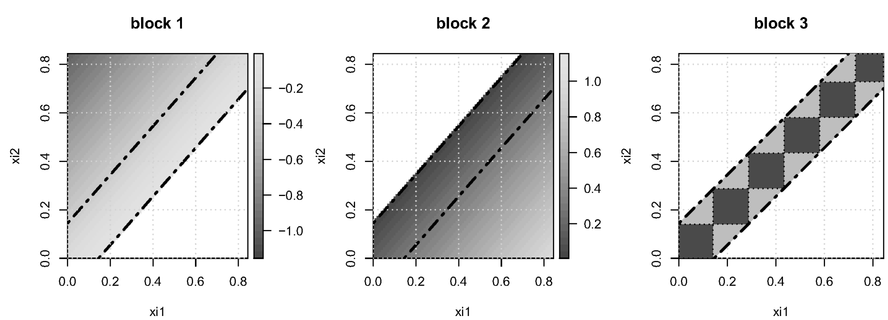

Figure 6: *Scenario 1* - The set of (ξ_1, ξ_2) associated with $\alpha^* = 0.71$.

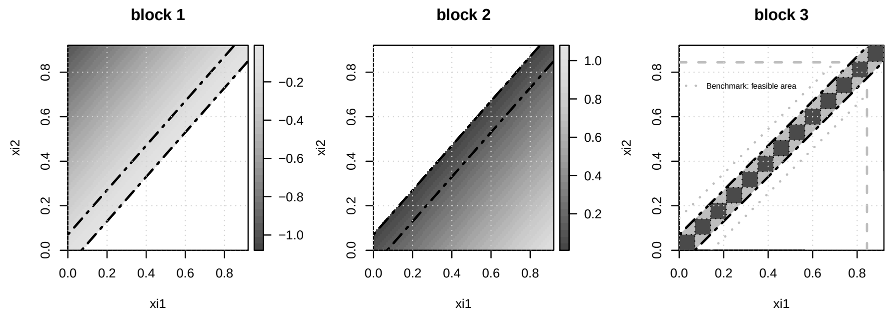

Figure 7: *Scenario 1* - The set of (ξ_1, ξ_2) associated with α^*: comparative statics on q.

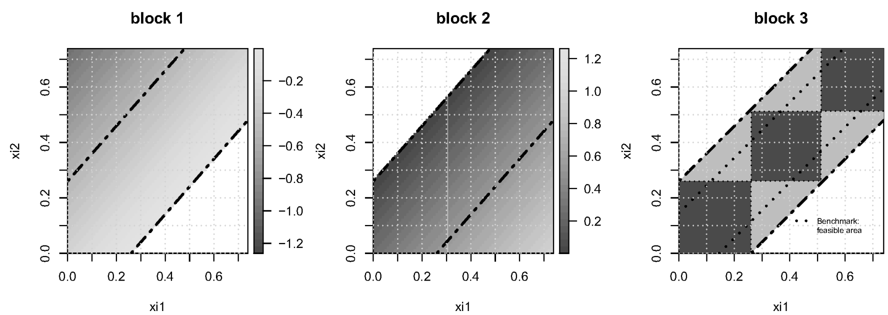

Figure 8: *Scenario 1* - The set of (ξ_1, ξ_2) associated with α^*: comparative statics on $LCOE$.

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 energy exchange P2P

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 NPV 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 to consider the corner solutions (Appendix A.4).
Figures 10, 11 and 12 provide graphical representations of each set of the scenario's constraints [48] and the resulting ranges of ξ_1 and ξ_2 associated with a feasible solution for each corner solution. The expected NPV 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, ii) 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 of 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 and 16, respectively. [49]

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, with respect to Scenario 1, that the prosumers' self-consumption profiles are allowably to be more disparate.

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

[48] Where the first and second blocks also represent the prosumers' optimal capacities.

[49] For brevity, we do not present the comparative statics relative to corner solution 2 since they are specular to those relative to corner solution 1.

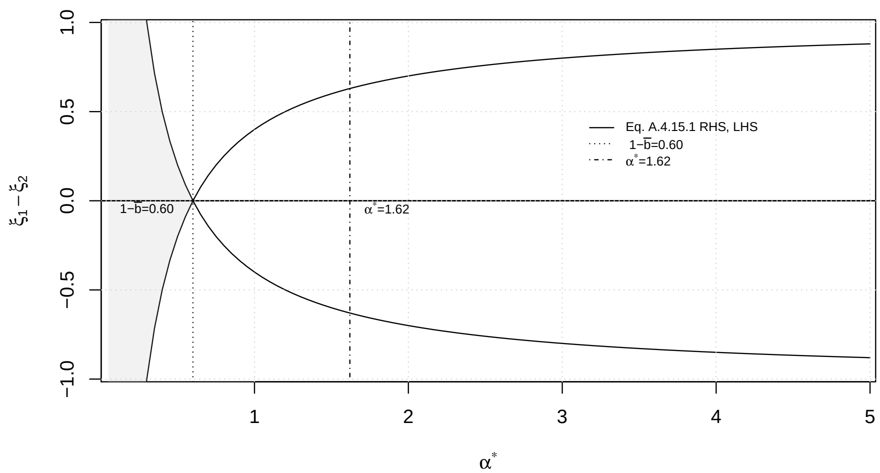

Figure 9: *Scenario 2* - The set of (ξ_1, ξ_2) associated with a feasible solution.

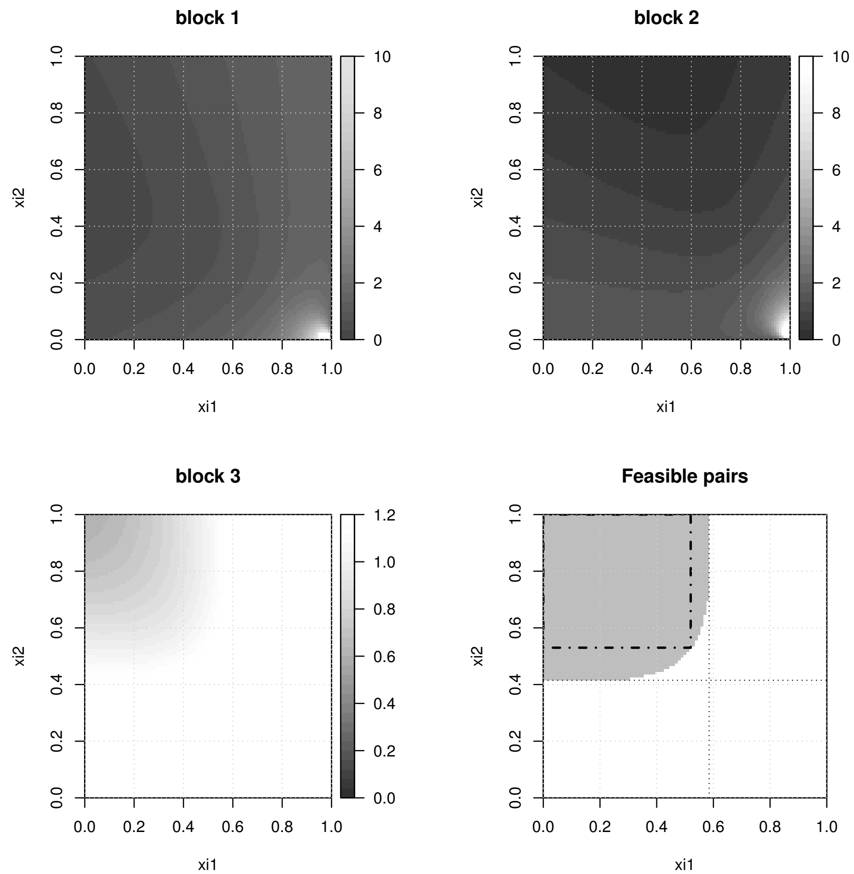

Figure 10: *Scenario 2* - Corner solution 1: constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution. Blocks 1 and 2 results from considering Eqs. (A.4.25.1) and (A.4.25.2) respectively. Block 3 results from considering Eq. (A.4.25.3). The last block shows the pairs of ξ_1 and ξ_2 associated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

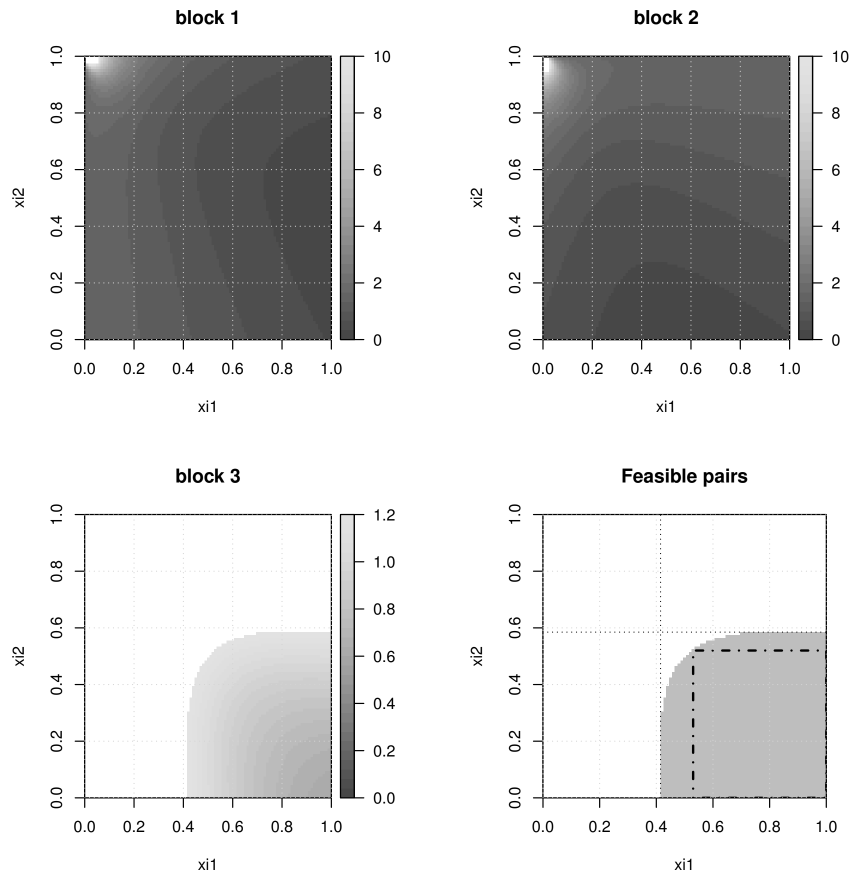

Figure 11: *Scenario 2* - Corner solution 2: constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution. Blocks 1 and 2 results from considering Eqs. (A.4.35.1) and (A.4.35.2), respectively. Block 3 results from considering Eq. (A.4.35.3). The last block shows the pairs of ξ_1 and ξ_2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

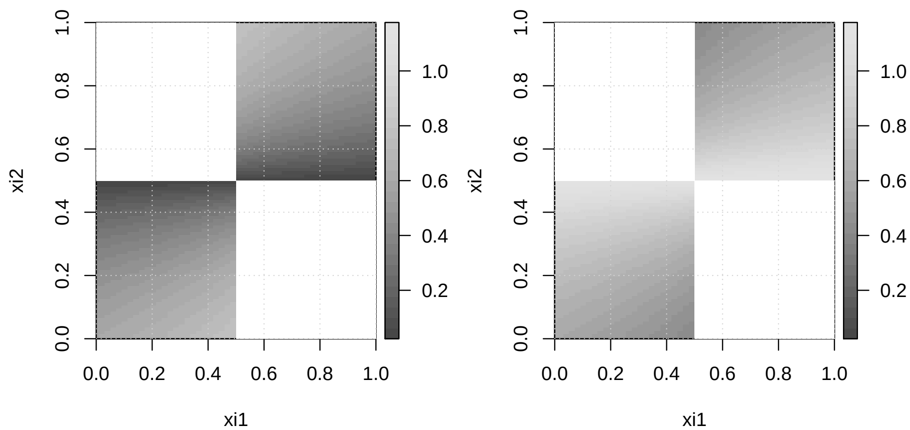

Figure 12: *Scenario 2* - Corner solution 3: constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution. Blocks 1 and 2 results from considering Eqs. (A.4.37) and (A.4.38), respectively.

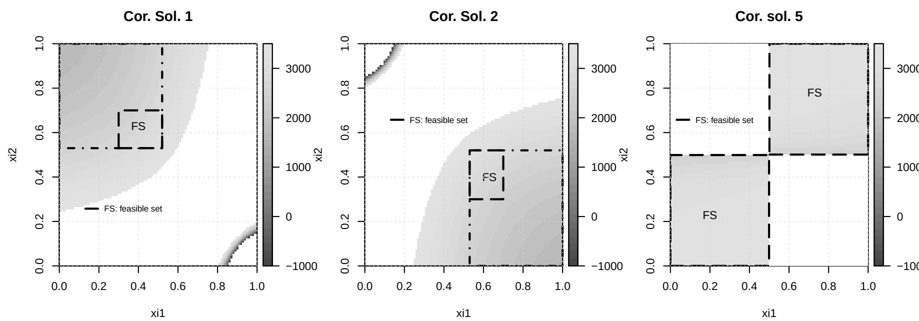

Figure 13: *Scenario 2* - Expected net present values. Blocks 1, 2 and 3 refer to corner solution 1, 2 and 3 respectively. The feasible sets (FS) are identified considering only the pairs of the ξ_i associated with the highest level of expected net present value.

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
$\mathcal{O}(\alpha_1^*, \alpha_2^*)$	2823	2823	3098	3098

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

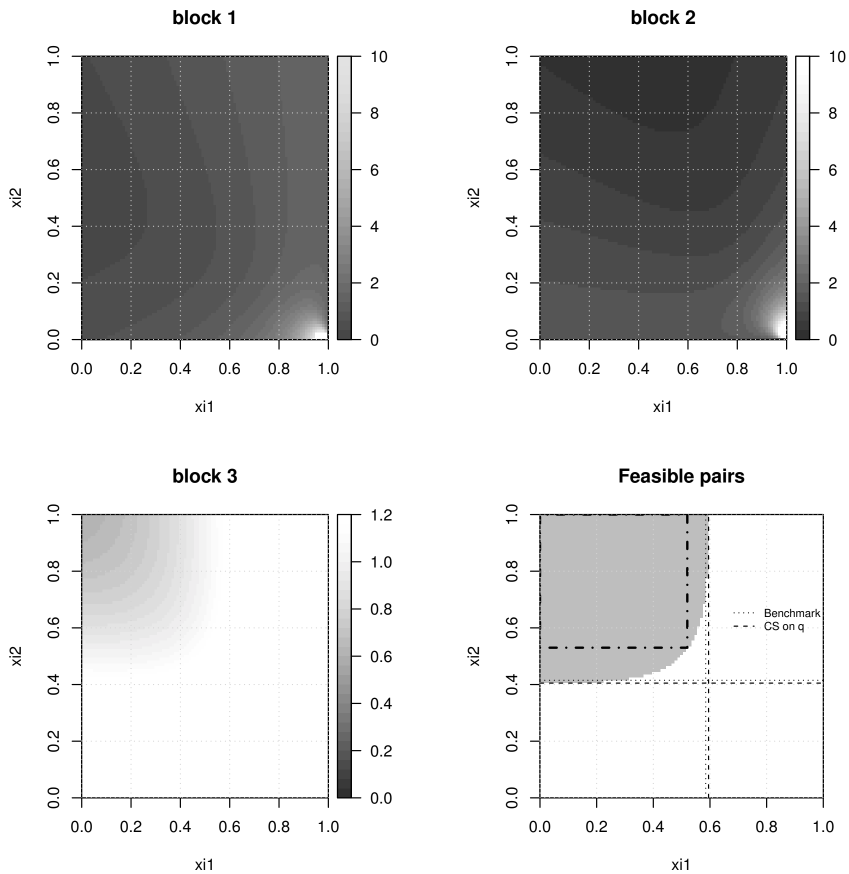

Figure 14: *Scenario 2* - Corner solution 1: constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution when $q_t = 54$.

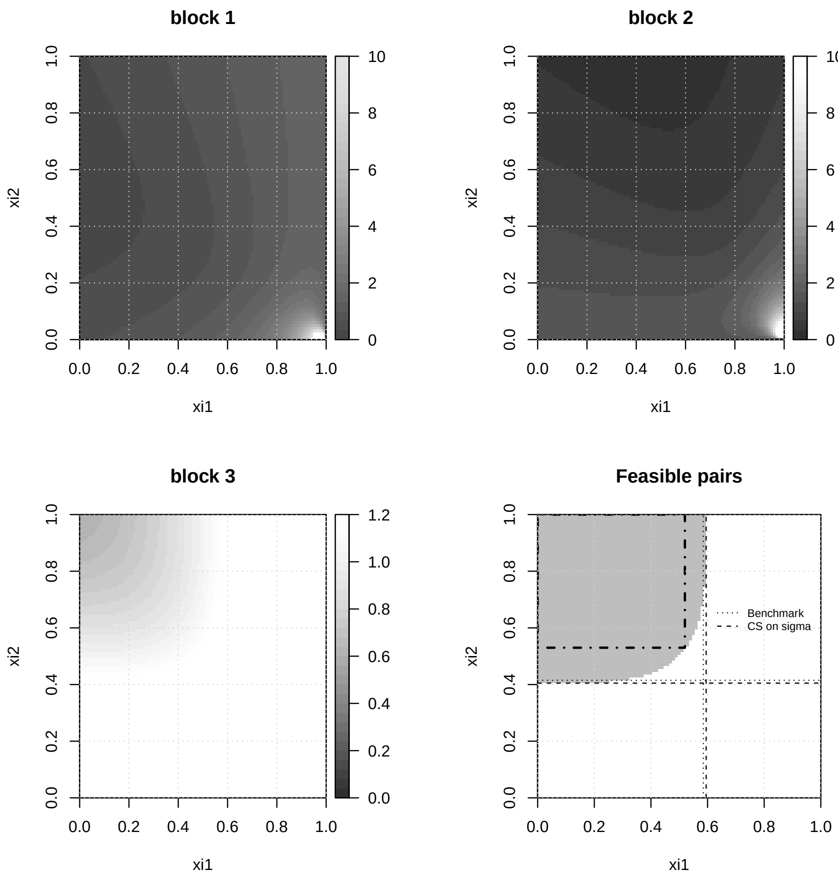

Figure 15: *Scenario 2* - Corner solution 1: constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution when $\sigma = 0.25$.

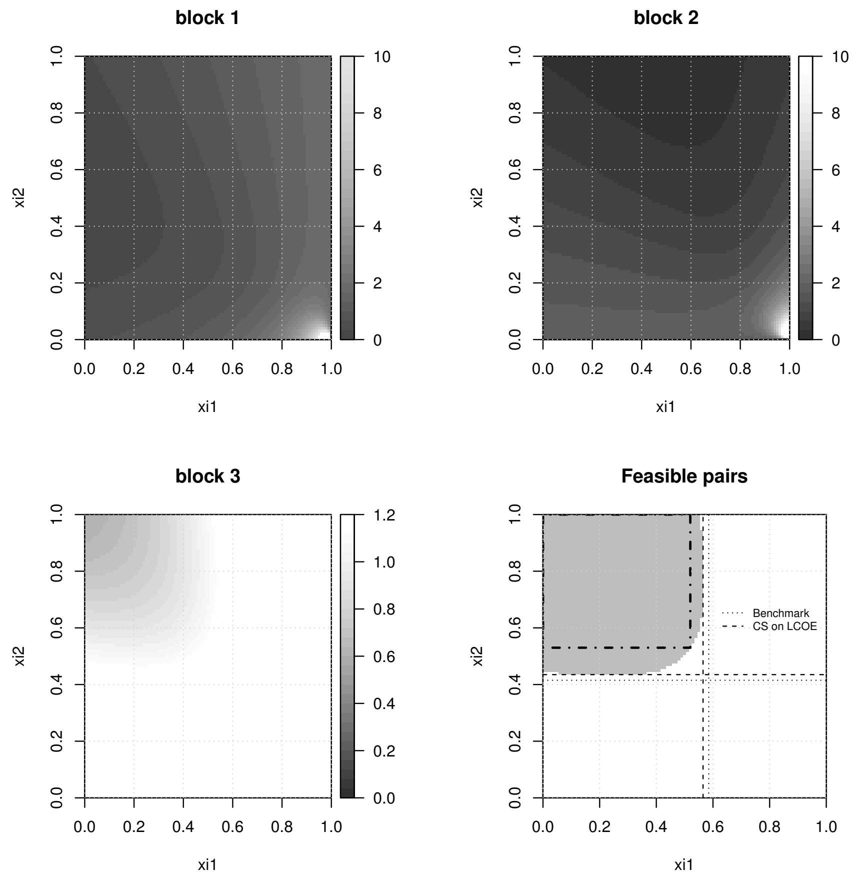

Figure 16: *Scenario 2* - Corner solution 1: constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution when $LCOE = 70$.

A.5.3 Scenario 3: non complementarity in the energy exchange P2P

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. [50] The area satisfying 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 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 the 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, as the optimal capacities decrease, prosumer 1 self-consumes less while prosumer 2 self-consumes more. On exchanged quantities, the effect is the opposite. Overall, prosumers gain less from investing in the PV project.
A decrease in σ widens 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.

[50] 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 follows: $\xi_1\alpha_1^* + (1-\xi_2)\,\alpha_2^* - (1-\bar{b}) > 0$ and $(1-\xi_1)\,\alpha_1^* + \xi_2\alpha_2^* - (1-\bar{b}) < 0$. The constraints' graphical representation is obtained by letting ξ_1 and ξ_2 vary over the range from 0 to 1.

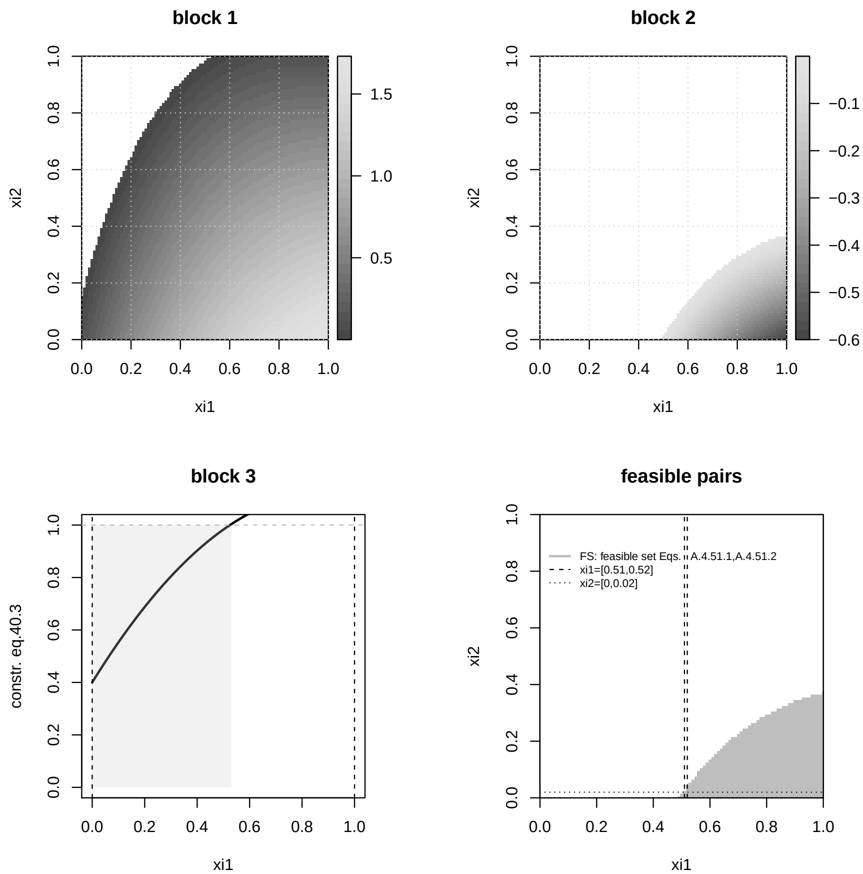

Figure 17: *Scenario 3* - Constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution. Block 1 results from considering Eq. (A.4.51.1), block 2 results from considering Eq. (A.4.51.2) and block 3 results from considering Eq. (A.4.51.3). Block 4 shows the pairs of ξ_1 and ξ_2 associated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

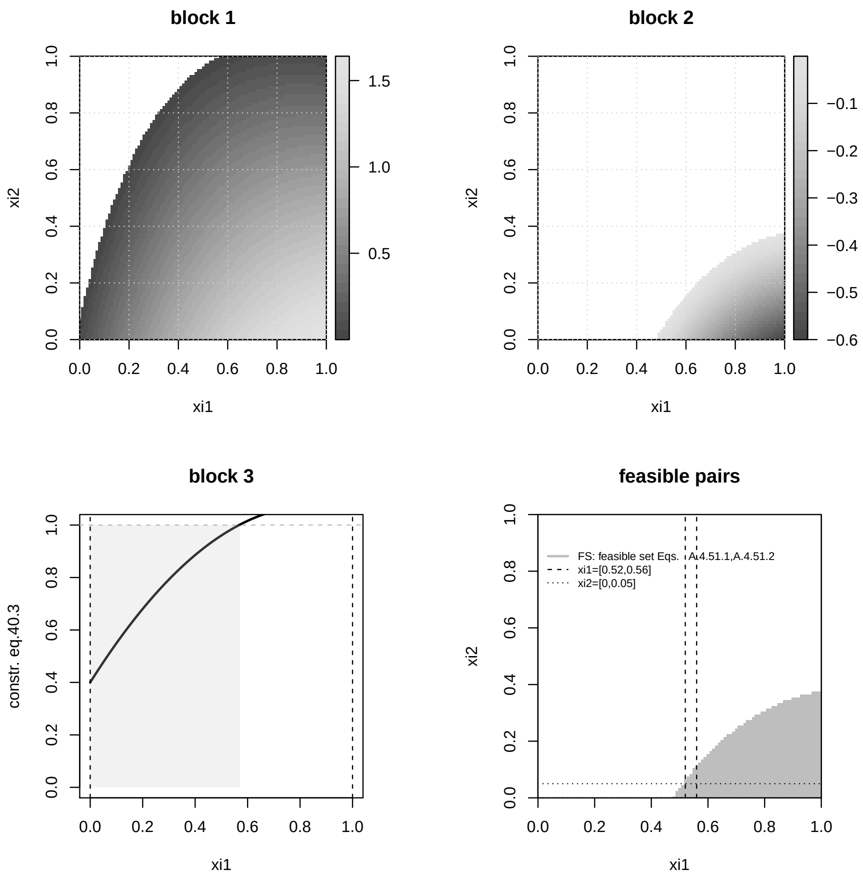

Figure 18: *Scenario 3* - Constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution when $q_t = 54$. Block 1 results from considering Eq. (A.4.51.1), block 2 results from considering Eq. (A.4.51.2) and block 3 results from considering Eq. (A.4.51.3). Block 4 shows the pairs of ξ_1 and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

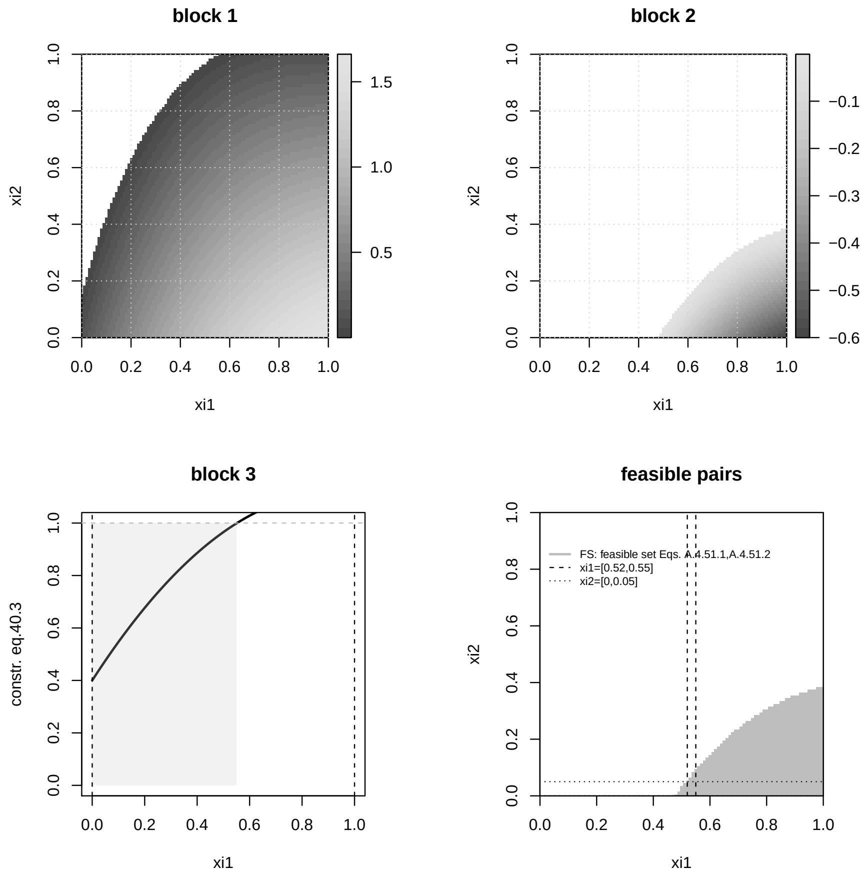

Figure 19: *Scenario 3* - Constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution when $\sigma = 0.25$. Block 1 results from considering Eq. (A.4.51.1), block 2 results from considering Eq. (A.4.51.2) and block 3 results from considering Eq. (A.4.51.3). Block 4 shows the pairs of ξ_1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

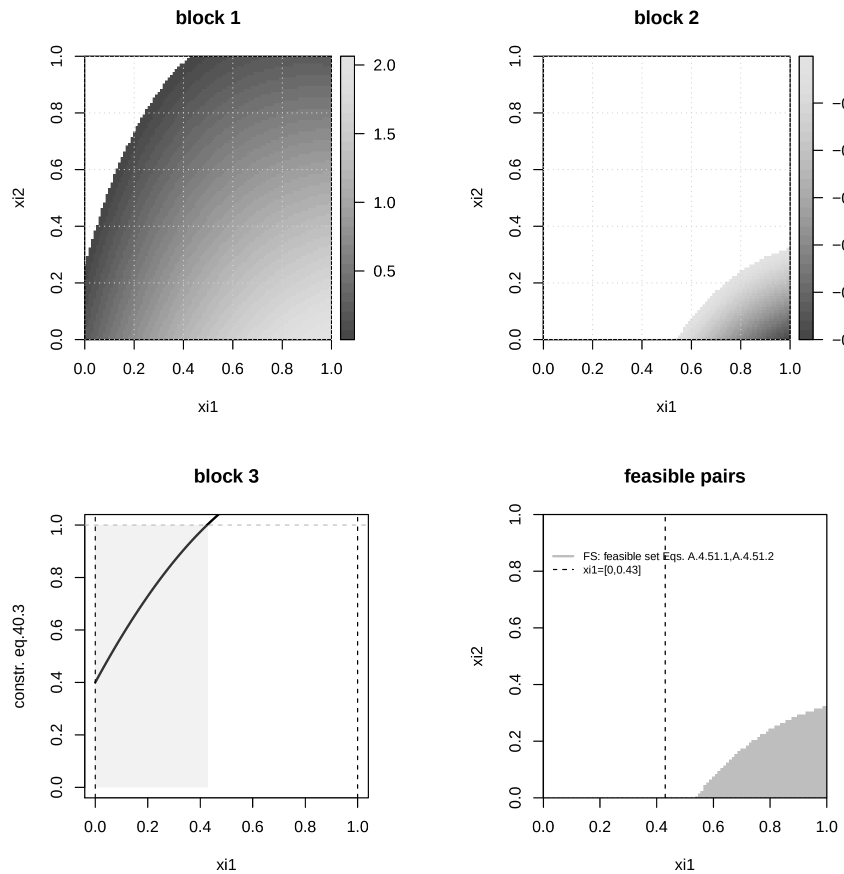

Figure 20: *Scenario 3* - Constraints and pairs of ξ_1 and ξ_2 associated with the optimal solution when $LCOE = 70$. Block 1 results from considering Eq. (A.4.51.1), block 2 results from considering Eq. (A.4.51.2) and block 3 results from considering Eq. (A.4.51.3). Block 4 shows the pairs of ξ_1 and 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	-
$\mathcal{O}(\alpha_1^*, \alpha_2^*)$	3012	2808	2811	-

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

References

Alam, M., Ramchurn, S. D., and Rogers, A. (2013). Cooperative energy exchange for the efficient use of energy and resources in remote communities. In *Proceedings of the 2013 international conference on Autonomous agents and multi-agent systems*, pages 731–738. International Foundation for Autonomous Agents and Multiagent Systems. 22

Alam, M. R., St-Hilaire, M., and Kunz, T. (2017). An optimal p2p energy trading model for smart homes in the smart grid. *Energy Efficiency*, 10(6):1475–1493. 1, 9

Andreis, L., Flora, M., Fontini, F., and Vargiolu, T. (2020). Pricing reliability options under different electricity price regimes. *Energy Economics*, 87:104705. 21

Angelidakis, A. and Chalkiadakis, G. (2015). Factored mdps for optimal prosumer decision-making. In *Proceedings of the 2015 International Conference on Autonomous Agents and Multiagent Systems*, pages 503–511. International Foundation for Autonomous Agents and Multiagent Systems. 1, 12

Bayod-Rújula, A., Burgio, A., Dominguez-Navarro, J., Mendicino, L., Menniti, D., Pinnarelli, A., Sorrentino, N., and Yusta-Loyo, J. (2017). Prosumers in the regulatory framework of two eu members: Italy and spain. In *2017 IEEE 14th International Conference on Networking, Sensing and Control (ICNSC)*, pages 25–30. IEEE. 12

Bellekom, S., Arentsen, M., and van Gorkum, K. (2016). Prosumption and the distribution and supply of electricity. *Energy, sustainability and society*, 6(1):22. 1, 19

Bertolini, M., D'Alpaos, C., and Moretto, M. (2018). Do smart grids boost investments in domestic pv plants? evidence from the italian electricity market. *Energy*, 149:890–902. 6, 1, 18, 25, 5, **??**, **??**

Boomsma, T. K., Meade, N., and Fleten, S.-E. (2012). Renewable energy investments under different support schemes: A real options approach. *European Journal of Operational Research*, 220(1):225–237. 12

Borovkova, S. and Schmeck, M. D. (2017). Electricity price modeling with stochastic time change. *Energy Economics*, 63:51–65. 21

Branker, K., Pathak, M., and Pearce, J. M. (2011). A review of solar photovoltaic levelized cost of electricity. *Renewable and sustainable energy reviews*, 15(9):4470–4482. 37, **??**

Bussar, C., Stocker, P., Cai, Z., Moraes Jr, L., Magnor, D., Wiernes, P., van Bracht, N., Moser, A., and Sauer, D. U. (2016). Large-scale integration of renewable energies and impact on storage demand in a european renewable power system of 2050. *Journal of Energy Storage*, 6:1–10. 1

Cambini, C., Meletiou, A., Bompard, E., and Masera, M. (2016). Market and regulatory factors influencing smart-grid investment in europe: Evidence from pilot projects and implications for reform. *Utilities Policy*, 40:36–47. 1

Campagna, N., Caruso, M., Castiglia, V., Miceli, R., and Viola, F. (2020). Energy management concepts for the evolution of smart grids. In *2020 8th International Conference on Smart Grid (icSmartGrid)*, pages 208–213. IEEE. 2, 12

Castellini, M., Menoncin, F., Moretto, M., and Vergalli, S. (2021). Photovoltaic smart grids in the prosumers investment decisions: a real option model. *Journal of Economic Dynamics and Control*, 126:103988. 6, 1, 15

Ceseña, E. M., Mutale, J., and Rivas-Dávalos, F. (2013). Real options theory applied to electricity generation projects: A review. *Renewable and Sustainable Energy Reviews*, 19:573–581. 12

Ciabattoni, L., Grisostomi, M., Ippoliti, G., and Longhi, S. (2014). Fuzzy logic home energy consumption modeling for residential photovoltaic plant sizing in the new italian scenario. *Energy*, 74:359–367. 12

Cox, J. C. and Ross, S. A. (1976). The valuation of options for alternative stochastic processes. *Journal of financial economics*, 3(1-2):145–166. 26

De Sisternes, F. J., Jenkins, J. D., and Botterud, A. (2016). The value of energy storage in decarbonizing the electricity sector. *Applied Energy*, 175:368–379. 27

Dixit, A. (1989). Entry and exit decisions under uncertainty. *Journal of political Economy*, 97(3):620–638. A.2

Ecker, F., Hahnel, U. J., and Spada, H. (2017). Promoting decentralized sustainable energy systems in different supply scenarios: the role of autarky aspiration. *Frontiers in Energy Research*, 5:14. 1

ESG, M. P. (2016). Renewable energy report 2016. Technical report, Energy & Strategy Group of Polytechnic University of Milan. 27

Espe, E., Potdar, V., and Chang, E. (2018). Prosumer communities and relationships in smart grids: A literature review, evolution and future directions. *Energies*, 11(10):2528. 1

EU (2018). Directive (eu) 2018/2001 of the european parliament and of the council. 10

Farmanbar, M., Parham, K., Arild, Ø., and Rong, C. (2019). A widespread review of smart grids towards smart cities. *Energies*, 12(23):4484. 12

Feng, S., Zhang, J., and Gao, Y. (2016). Investment uncertainty analysis for smart grid adoption: A real options approach. *Information Polity*, 21(3):237–253. 2, 12

Ghosh, A., Aggarwal, V., and Wan, H. (2018). Exchange of renewable energy among prosumers using blockchain with dynamic pricing. *arXiv preprint arXiv:1804.08184*. 1, 12

Gianfreda, A. and Grossi, L. (2012). Forecasting italian electricity zonal prices with exogenous variables. *Energy Economics*, 34(6):2228–2239. 32

Gonzalez-Romera, E., Ruiz-Cortes, M., Milanes-Montero, M.-I., Barrero-Gonzalez, F., Romero-Cadaval, E., Lopes, R. A., and Martins, J. (2019). Advantages of minimizing energy exchange instead of energy cost in prosumer microgrids. *Energies*, 12(4):719. 1, 12

Hahnel, U. J., Herberz, M., Pena-Bello, A., Parra, D., and Brosch, T. (2020). Becoming prosumer: Revealing trading preferences and decision-making strategies in peer-to-peer energy communities. *Energy Policy*, 137:111098. 12

Harsanyi, J. (1977). Rational behavior and bargaining equilibrium in games and social situations (cambridge up, cambridge). A.1

Hernández-Callejo, L. (2019). A comprehensive review of operation and control, maintenance and lifespan management, grid planning and design, and metering in smart grids. *Energies*, 12(9):1630. 11

InterregEU, E. (2018). Policy brief on low-carbon economy. Technical report, European Union. 9

Ioannou, A., Angus, A., and Brennan, F. (2017). Risk-based methods for sustainable energy system planning: A review. *Renewable and Sustainable Energy Reviews*, 74:602–615. 12

Jiménez-Castillo, G., Muñoz-Rodriguez, F., Rus-Casas, C., and Talavera, D. (2019). A new approach based on economic profitability to sizing the photovoltaic generator in self-consumption systems without storage. *Renewable Energy*. 1

Kästel, P. and Gilroy-Scott, B. (2015). Economics of pooling small local electricity prosumers - lcoe & self-consumption. *Renewable and Sustainable Energy Reviews*, 51:718–729. 12, 37, **??**

Kozlova, M. (2017). Real option valuation in renewable energy literature: Research focus, trends and design. *Renewable and Sustainable Energy Reviews*, 80:180–196. 12, 21

Kriett, P. O. and Salani, M. (2012). Optimal control of a residential microgrid. *Energy*, 42(1):321–330. 12

Lazard (2020). Levelized cost of energy analysis. version 14.0. Technical report, Lazard. 38, **??**

Liu, T., Tan, X., Sun, B., Wu, Y., and Tsang, D. H. (2018). Energy management of cooperative microgrids: A distributed optimization approach. *International Journal of Electrical Power & Energy Systems*, 96:335–346. 1, 12

Luo, Y., Itaya, S., Nakamura, S., and Davis, P. (2014). Autonomous cooperative energy trading between prosumers for microgrid systems. pages 693–696. 1, 9

Luthander, R., Widen, J., Nilsson, D., and Palm, J. (2015). Photovoltaic self-consumption in buildings: A review. *Applied Energy*, 142:80 – 94. 1, 12, 2, **??**

Martinez-Cesena, E. A., Azzopardi, B., and Mutale, J. (2013). Assessment of domestic photovoltaic systems based on real options theory. *Progress in Photovoltaics: Research and Applications*, 21(2):250–262. 12

Masson, G., Briano, J. I., and Baez, M. J. (2016). A methodology for the analysis of pv self-consumption policies. *International Energy Agency. Paris, France*. 1

Mengelkamp, E., Staudt, P., Garttner, J., and Weinhardt, C. (2017). Trading on local energy markets: A comparison of market designs and bidding strategies. In *2017 14th International Conference on the European Energy Market (EEM)*, pages 1–6. IEEE. 22

Mercure, J.-F. and Salas, P. (2012). An assessement of global energy resource economic potentials. *Energy*, 46(1):322–336. 25

Mishra, S., Bordin, C., Tomasgard, A., and Palu, I. (2019). A multi-agent system approach for optimal microgrid expansion planning under uncertainty. *International Journal of Electrical Power & Energy Systems*, 109:696–709. 1

Mondol, J. D., Yohanis, Y. G., and Norton, B. (2009). Optimising the economic viability of grid-connected photovoltaic systems. *Applied Energy*, 86(7-8):985–999. 12, 19

Moreno, R., Street, A., Arroyo, J. M., and Mancarella, P. (2017). Planning low-carbon electricity systems under uncertainty considering operational flexibility and smart grid technologies. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 375(2100):20160305. 2, 12

Morstyn, T., Farrell, N., Darby, S. J., and McCulloch, M. D. (2018). Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants. *Nature Energy*, 3(2):94. 1

Nash, J. (1950). The bargaining problem. *Econometrica: Journal of the econometric society*, pages 155–162. A.1

Nash, J. (1953). Two-person cooperative games. *Econometrica*, 21(1):128–140. A.1

Oren, S. S. (2001). Integrating real and financial options in demand-side electricity contracts. *Decision Support Systems*, 30(3):279–288. 12

Ottesen, S. Ø., Tomasgard, A., and Fleten, S.-E. (2016). Prosumer bidding and scheduling in electricity markets. *Energy*, 94:828–843. 12

Paetz, A.-G., Becker, B., Fichtner, W., Schmeck, H., et al. (2011). Shifting electricity demand with smart home technologies–an experimental study on user acceptance. In *30th USAEE/IAEE North American conference online proceedings*, volume 19, page 20. 12

Parag, Y. and Sovacool, B. K. (2016). Electricity market design for the prosumer era. *Nature energy*, 1(4):16032. 1

Peloso, D. (2018). Logiche ottimizzate per la gestione di sistemi di accumulo in comunità energetiche: il caso studio regalgrid presso h-farm. 39, **??**

Pillai, G. G., Putrus, G. A., Georgitsioti, T., and Pearsall, N. M. (2014). Near-term economic benefits from grid-connected residential pv (photovoltaic) systems. *Energy*, 68:832–843. 12, 19

Razzaq, S., Zafar, R., Khan, N., Butt, A., and Mahmood, A. (2016). A novel prosumer-based energy sharing and management (pesm) approach for cooperative demand side management (dsm) in smart grid. *Applied Sciences*, 6(10):275. 1

Saad al sumaiti, A., Ahmed, M. H., and Salama, M. M. (2014). Smart home activities: A literature review. *Electric Power Components and Systems*, 42(3-4):294–305. 1

Salpakari, J. and Lund, P. (2016). Optimal and rule-based control strategies for energy flexibility in buildings with pv. *Applied Energy*, 161:425–436. 12

Schachter, J. and Mancarella, P. (2016). A critical review of real options thinking for valuing investment flexibility in smart grids and low carbon energy systems. *Renewable and Sustainable Energy Reviews*, 56:261–271. 1, 12

Schachter, J. A. and Mancarella, P. (2015). Demand response contracts as real options: a probabilistic evaluation framework under short-term and long-term uncertainties. *IEEE Transactions on Smart Grid*, 7(2):868–878. 1

Schachter, J. A., Mancarella, P., Moriarty, J., and Shaw, R. (2016). Flexible investment under uncertainty in smart distribution networks with demand side response: assessment framework and practical implementation. *Energy Policy*, 97:439–449. 12

Sezgen, O., Goldman, C., and Krishnarao, P. (2007). Option value of electricity demand response. *Energy*, 32(2):108–119. 12

Sommerfeldt, N. and Madani, H. (2017). Revisiting the techno-economic analysis process for building-mounted, grid-connected solar photovoltaic systems: Part two-application. *Renewable and Sustainable Energy Reviews*, 74:1394–1404. 1

Sousa, T., Soares, T., Pinson, P., Moret, F., Baroche, T., and Sorin, E. (2019). Peer-to-peer and community-based markets: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 104:367–378. 1, 9

Sun, Q., Beach, A., Cotterell, M. E., Wu, Z., and Grijalva, S. (2013). An economic model for distributed energy prosumers. In *2013 46th Hawaii International Conference on System Sciences*, pages 2103–2112. IEEE. 12

Talavera, D., Muñoz-Rodriguez, F., Jimenez-Castillo, G., and Rus-Casas, C. (2019). A new approach to sizing the photovoltaic generator in self-consumption systems based on cost–competitiveness, maximizing direct self-consumption. *Renewable energy*, 130:1021–1035. 1

Tian, L., Pan, J., Du, R., Li, W., Zhen, Z., and Qibing, G. (2017). The valuation of photovoltaic power generation under carbon market linkage based on real options. *Applied energy*, 201:354–362. 12

Tveten, Å. G., Bolkesjø, T. F., Martinsen, T., and Hvarnes, H. (2013). Solar feed-in tariffs and the merit order effect: A study of the german electricity market. *Energy Policy*, 61:761–770. 25

Velik, R. and Nicolay, P. (2016). Energy management in storage-augmented, grid-connected prosumer buildings and neighborhoods using a modified simulated annealing optimization. *Computers & Operations Research*, 66:248–257. 19

Weniger, J., Tjaden, T., Quaschning, V., et al. (2014). Sizing of residential pv battery systems. *Energy Procedia*, 46(Suppl. C):78–87. **??**

Zafar, R., Mahmood, A., Razzaq, S., Ali, W., Naeem, U., and Shehzad, K. (2018). Prosumer based energy management and sharing in smart grid. *Renewable and Sustainable Energy Reviews*, 82:1675–1684. 1, 9, 12, 22

Zhang, C., Wu, J., Zhou, Y., Cheng, M., and Long, C. (2018). Peer-to-peer energy trading in a microgrid. *Applied Energy*, 220:1–12. 1, 9
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