October 2019

Working Paper

028.2019

Photovoltaic Smart Grids in the Prosumers Investment Decisions: a Real Option Model

Marta Castellini, Francesco Menoncin, Michele Moretto, Sergio Vergalli

Economics for Sustainability
Series Editor: Sergio Vergalli

Photovoltaic Smart Grids in the Prosumers Investment Decisions: a Real Option Model

By Marta Castellini, Università degli Studi di Brescia and Fondazione Eni Enrico Mattei
Francesco Menoncin, Università degli Studi di Brescia
Michele Moretto, Università degli Studi di Padova
Sergio Vergalli, Università degli Studi di Brescia and Fondazione Eni Enrico Mattei

Summary

The digitization of power system represents one of the main instruments to achieve the target set by the European Union 2030 climate and energy Agenda of affordable energy transition. During the last years, such innovation process has been associated with the Smart Grid (SG) term. In this context, efficiency and flexibility of power systems are expected to increase and energy consumers to be active also on the production side, thus becoming prosumers (agents that both produce and consume energy). This paper provides a theoretical real option framework with the aim to model prosumers' decision to invest in photovoltaic power plants, assuming that they are integrated in a Smart Grid. Our main focus is to study the optimal plant size and the optimal investment threshold, in a context where exchange of energy among prosumers is possible. The model was calibrated and tested with data from the Northern Italy energy market. Our findings show that the possibility of selling energy between prosumers, via the Smart Grid, increases investment values. This opportunity encourages prosumers to invest in a larger plant compared with the case without exchange possibility and that there is a positive relation between optimal size and (optimal) investment timing. The effect of uncertainty is in line with the literature, showing increasing value to defer with volatility.

Keywords: Smart Grids, Renewable Energy Sources, Real Options, Prosumer, Peer to Peer Energy Trading

JEL Classification: Q42, C61, D81

Address for correspondence:
Sergio Vergalli
Università degli Studi di Brescia
Department of Economics and Management
via S. Faustino, 74/B
25122 Brescia
Italy
E-mail: sergio.vergalli@unibs.it

Photovoltaic Smart Grids in the prosumers investment decisions: a real option model

Marta Castellini* Francesco Menoncin† Michele Moretto‡ Sergio Vergalli§

Abstract

The digitization of power system represents one of the main instruments to achieve the target set by the European Union 2030 climate and energy Agenda of affordable energy transition. During the last years, such innovation process has been associated with the Smart Grid (SG) term. In this context, efficiency and flexibility of power systems are expected to increase and energy consumers to be active also on the production side, thus becoming prosumers (agents that both produce and consume energy). This paper provides a theoretical real option framework with the aim to model prosumers' decision to invest in photovoltaic power plants, assuming that they are integrated in a Smart Grid. Our main focus is to study the optimal plant size and the optimal investment threshold, in a context where exchange of energy among prosumers is possible. The model was calibrated and tested with data from the Northern Italy energy market. Our findings show that the possibility of selling energy between prosumers, via the Smart Grid, increases investment values. This opportunity encourages prosumers to invest in a larger plant compared with the case without exchange possibility and that there is a positive relation between optimal size and (optimal) investment timing. The effect of uncertainty is in line with the literature, showing increasing value to defer with volatility.

Keywords: Smart Grids, Renewable Energy Sources, Real Options, Prosumer, Peer to Peer Energy Trading.

JEL Classification: Q42, C61, D81

*marta.castellini@unibs.it - Department of Economics and Management, Università degli Studi di Brescia, Via S. Faustino 74/B – 25122 Brescia – Italy,
FEEM - Fondazione Eni Enrico Mattei, Corso Magenta 63, Milan, Italy

†francesco.menoncin@unibs.it - Department of Economics and Management, Università degli Studi di Brescia, Via S. Faustino 74/B – 25122 Brescia – Italy

‡michele.moretto@unipd.it - Department of Economics and Management, Università degli Studi di Padova, Via del Santo 33, Padova

§sergio.vergalli@unibs.it - Department of Economics and Management, Università degli Studi di Brescia, Via S. Faustino 74/B – 25122 Brescia – Italy,
FEEM - Fondazione Eni Enrico Mattei, Corso Magenta 63, Milan, Italy

1 Introduction

In recent years climate change has become an important issue in the economic debate. The latest IPCC[1] report IPCC, 2019 underlines how important is the control of temperature levels by reducing or limiting CO2 emissions. This could avoid the occurrence of irreversible effects. Some mitigation paths are characterized by the reductions in energy demand, decarbonization of electricity and other fuels, electrification of the final use of energy. In this line, the European Union 2030 climate and energy policy has set three macro targets: the reduction of 40% in greenhouse gas emissions (from 1990 levels), 32% of renewable energy and an improvement in energy efficiency of 32.5%, whereas the long-term strategy aims to reach a climate neutral economy within 2050 [2].

Such policies require strong deployment of low carbon technologies as well as an adequate efficient environment[3]. A central role is played by the definition of new emerging power system, required to be decarbonized, decentralized and digitized. Decarbonization is also related to the diffusion of renewable energy plants, while decentralization refers to the growing role of new electricity producers, characterized by a large number, with small-scale and decentralized and intermittent periods of overproduction of electricity, mostly photovoltaic (PV, hereafter). Finally, digitization implies the innovation of the power system, a concept that has also been associated in the last years to the Smart Grids (SGs, hereafter)[4] that are "robust, self-healing networks that allow bidirectional propagation of energy and information within the utility grid". This last element plays an important role, since technological development enables also an affordable energy transition.

In this respect, the continuous integration of Distributed Energy Resources (DERs, hereafter) (Sousa et al., 2019; Bussar et al., 2016; Zhang et al., 2018),[5] along with the advance in Information and Communication Technology (ICT) devices (Saad al sumaiti et al., 2014) are inducing a transformation of a share of electricity consumers who **pro**duce and con**sume** and share energy with other grid users. Such users are called "**prosumers**" (Luo et al., 2014; Sommerfeldt and Madani, 2017; Espe et al., 2018; Zafar et al., 2018).

Smart grids actually introduce the possibility of adopting new behaviors: while traditional consumers assume a passive behavior in buying and receiving energy from the grid, prosumers undertake a proactive one by managing their consumption and production (Zafar et al., 2018). Indeed, they can reduce their energy consumption costs, making self-consumption of the energy produced by their PV plants (Luthander et al., 2015; Masson et al., 2016). In addition to that, Espe et al. (2018) remark the importance of prosumers participation to the smart

[1]Intergovernmental Panel on Climate Change

[2]*Source*: `https://ec.europa.eu/clima/policies/strategies_en`

[3]Some laws of 2030 package refer in particular to the energy market from the revision of the Renewables Directive, of the Energy Efficiency Directive, also called Energy Performance of buildings Directive and the Electricity Market design.

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

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

grid as critical for sustainability and long term efficiency of the energy sharing process. Furthermore, SGs allow instantaneous interactions between agents and the grid: depending on its needs, the grid can send signals (through prices) to the agents , and agents can respond to those signals and obtain monetary gain as a counterpart. These two characteristics (self-consumption and energy exchange with national grid) can add flexibility that, in turn, increases investment value (Bertolini et al., 2018). A third important characteristic, that depends on the development of new technologies and digitalization, is the possibility to exchange energy also between agents (InterregEU, 2018; Luo et al., 2014; Alam et al., 2017; Zafar et al., 2018; Zhang et al., 2018), in a Peer-to-Peer (P2P, hereafter) energy trading or in developing energy communities (Sousa et al., 2019). P2P energy trading 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). Energy communities can involve groups of citizens, social entrepreneurs, public authorities and community organization participating directly in the energy transition by jointly investing in, producing, selling and distributing renewable energy. This can introduce further flexibility to the investment that could add value, depending on the adoption costs of the new technology and the shape of load (demand) electricity curve of agents. Therefore it is interesting to study if this additional flexibility could have value, in which manner this could affect the investment decisions and if it can be supported by data.

In this paper, we examine whether the connection to the SG and the possibility to exchange energy among agents, can increase the investment value in a PV plant (i.e., investment profitability) and influence decisions regarding the optimal size of the plant. We model the investment decision of two small (price-takers) households end-user. Each agent is a prosumer (i.e., it is simultaneously a consumer and a producer) that can: a) self-consume its energy production; b) exchange energy with national grid and/or c) exchange energy with the other agent. Due to the high irreversibility and uncertainties over demand evolution, technological advances and an ever changing regulatory environment (Schachter and Mancarella, 2015; Schachter and Mancarella, 2016; Cambini et al., 2016), we implement a Real Option model to determine the optimal size and the overall investment value of a PV system characterized by the previous features. As consumers, the two agents can buy energy from the national grid or buy energy from the other agent or self-consume the energy produced by the PV plant. As producers, they may decide to collaborate with the local energy market manager to the grid equilibrium, by selling the whole energy produced or to sell the energy produced and not self-consumed to the national gird or to the other agent. In this respect, SGs may generate managerial flexibilities which prosumers can exercise optimally when deciding to invest. This flexibility gives them the option to decide strategically the optimal production/consumption energy pattern and can significantly contribute to energy saving and hedging the investment risk. To capture the value of managerial flexibility, we calibrate and test our model using data from the Italian electricity market.

In our work we combine decisions on irreversible investments under uncertainty with connections to an SG and with possibility of exchange between prosumers. In addition to this, we contribute to two strands of literature: first to the literature on SG technologies (Kriett and Salani, 2012), prosumers' behavior in energy markets (Ottesen et al., 2016, Bayod-Rújula et al., 2017), demand-side management (Oren, 2001, Salpakari and Lund, 2016), demand-response (Schachter and Mancarella, 2016, Sezgen et al., 2007), P2P and energy community[6]. Second, we complement the existing literature on the Real Options approach to investment decisions in the energy sector (Kozlova, 2017, Ceseña et al., 2013) and in PV plants (Martinez-Cesena et al., 2013,Tian et al., 2017) with a novel application in which we introduce prosumers exchanges in investments in domestic PV systems. Among contributions, the closest to our are: Bertolini et al. (2018) where the size of the optimal plant is identified with Real Options; Luo et al. (2014), in which exchange P2P is deepen in a Microgrid context under the assumption of storage possibility and its dynamic simulated to understand the impact of cooperative energy trading on renewable energy utilization; Zhang et al. (2018) which investigates the feasibility of P2P energy trading with flexible demand and focusing on the energy exchange between the Microgrid and the utility grid; Gonzalez-Romera et al. (2019) where the case of two households prosumers is investigated, even though the focus is on energy exchange minimization instead of energy cost. In this context the novelty of our paper is the study the value of flexibilities introduced by P2P energy community in a real option framework.

Our findings show that at current prices the possibility of selling energy between agents encourages investment in larger plants, compared with the cases without exchange. Moreover the value of exchange is always positive as well as the option value to defer investment. In addition to that our results show a positive relation between plant optimal size and optimal investment timing (i.e., the greater the plant optimal size, the greater the investment deferral). About uncertainty, increasing volatility rises the option value to defer and, in turn, increases the investment value. At the same time, with high volatility, the PV plant is built for selling and not for exchange purpose. Thus, an interesting policy implication for pushing energy community diffusion, is the stabilization of the energy prices volatility.

The rest of the paper is organized as follows. Section 2 describes the model

[6] A wide review of current literature in these topics is provided by Espe et al. (2018), focusing on prosumers community group and prosumers relationship, and Sousa et al. (2019) which deepen the aspects of the P2P energy market as *consumer-centric electricity market.* In both works relevant attention is drawn on the key role played by information and communication technology with two different perspectives: on the economics side, related to the definition of market structure and on the technological one, with reference to the concepts of the SG and Microgrid. Prosumers' behaviors in self consumption, exchange and investment choices are investigated through several optimization techniques (Zafar et al., 2018, Angelidakis and Chalkiadakis, 2015, Razzaq et al., 2016) and most of them focus on cost minimization (Liu et al., 2018). A different approach is provided instead by Gonzalez-Romera et al. (2019), in which the prosumers' benefit is determined by the minimizing of the exchange of energy instead of the energy cost and by Ghosh et al. (2018), where the price of exchanged P2P energy is defined with the aim to minimize the consumption of conventional energy, even though prosumers' aim is to minimize their own payoffs.

set-up. Section 3 introduces the calibration of the parameters, and Section 4 provides our main results and comparative statics. Section 5 concludes.

2 The model

In this model we investigate the case of two prosumers ($i = 1, 2$), currently connected to a national grid under a flat contract. Each agent has to decide whether and when to invest in a PV plant to cover part of his energy demand. Each prosumer may also decide to build a SG to connect his plant to the second prosumer and to the energy market, with the possibility of selling the energy produced to the other prosumer at price z and to the national provider at price v_t, where the latter is assumed to be stochastic. In addition to that, prosumers can also decide to buy energy directly from the national grid at a constant price c.

Before analyzing the investment decision, we introduce some simplifying assumptions:

2.1 Main assumptions

Assumption 1: prosumer's energy demand. The energy demand of prosumer i per unit of time t is normalized to 1 (i.e $1Mwh$) and can be covered as follows:

$$\begin{aligned} 1Mwh =& \xi_i \alpha_i + \gamma_i (1 - \xi_j) \alpha_j + b_i, \qquad \text{with } i \neq j = 1, 2, \\ &\text{where } \xi_i \in \left[0, \bar{\xi_i}\right], \\ &\qquad \gamma_i \in \left[0, \bar{\gamma_i}\right]. \end{aligned} \tag{1}$$

In (1) α_i is the expected production at each t associated with the capacity chosen by prosumer i, $\xi_i \alpha_i$ is the portion of α_i destined to self-consumption, where ξ_i is the self-consumption percentage of prosumer i, $\gamma_i (1 - \xi_j) \alpha_j$ is the quota satisfied by buying energy from the other prosumer j (exchange), where γ_i is the P2P exchange percentage of prosumer i, and b_i is the amount of energy that prosumer i purchases from the national provider. Finally, $\bar{\xi_i}$ and $\bar{\gamma_i}$ indicate the maximum self consumption and exchange percentages that are reasonably achieved with the photovoltaic system.[7].

Assumption 2: prosumers' behavior in exchange of energy choices. The two prosumers are assumed to be asymmetric in load curves, meaning that they behave complementarily in demand and supply of exchanged energy. Moreover, the demand of energy of each prosumer i in exchange process cannot exceed the quantity of energy that the other prosumer can sell. To better describe this

[7] The prosumer's self consumption depends on the load profile, the location and the renewable energy technology applied. In general it can be represented as a weakly concave function of α_i, i.e. $\xi_i(0)$, $\xi_i'(\alpha_i) > 0$ and $\xi_i''(\alpha_i) \leq 0$. However, many technical reports show that this quota does not exceed 30%-50% of production. Therefore for the sake of simplicity, we assume a linear function.

assumption, we show in Figure 2.1 an example of daily load and production curves for two prosumers. In the lower part of Figure 2.1, for each agent we show how the load curve is satisfied and how the exchange works among prosumers. In details, we show for agent i, the PV production represented by α_i, the self consumption quota, $\xi_i \alpha_i$, the energy shared between the two prosumers, $\gamma_i (1 - \xi_j) \alpha_j$, the quota bought from the national provider, b_i, and finally the excess of production that can be sold to the national grid. As it is possible to observe, even if the two agents have the same load and supply curves, they are asymmetric and can exchange energy. Moreover, according to this and our assumptions, self consumption and exchange among agents, counterbalance sales to national grid.

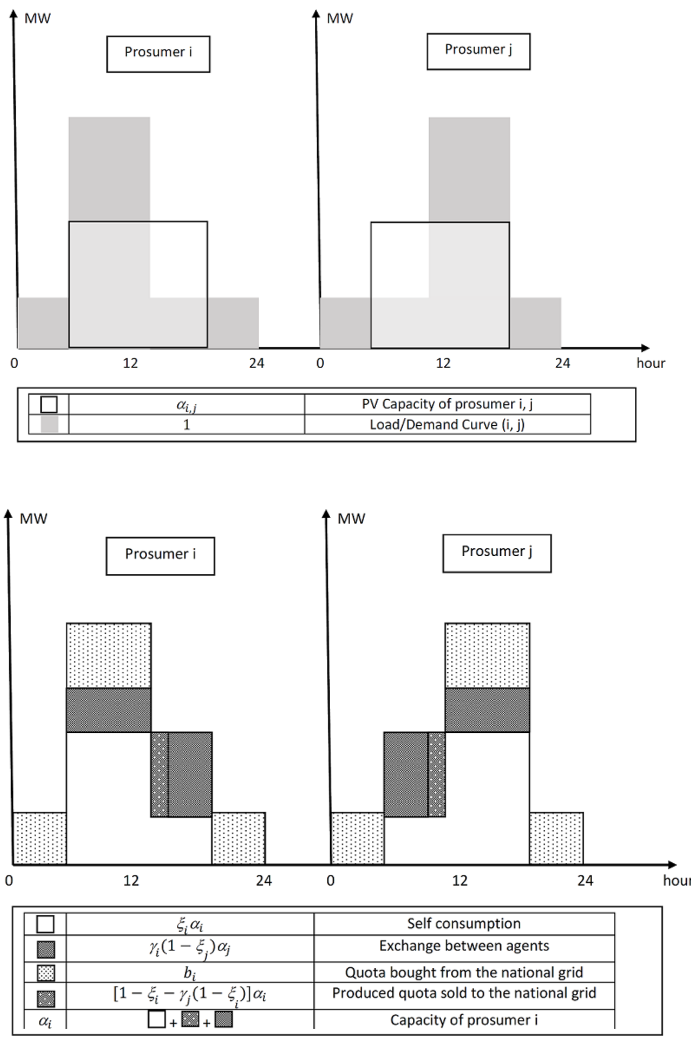

Figure 2.1: Daily load and production curves

Assumption 3: storage is not possible. According to De Sisternes et al. (2016) perspective, ESG (2016) and ESG (2018), storage technologies are still far to be cost effective, thus we assume that no battery is included in the investment. This choice allows to include a decrease in prosumers' managerial flexibility, since energy must be used as long as it is produced. From this follows $b_i > 0$.

Assumption 4: investment cost function. Prosumers cooperate in investment decision, meaning that at time $t = \tau$, where $\tau \in [0, +\infty)$, the investment cost function of the prosumers is

$$I(\alpha_1, \alpha_2) = P + \frac{K}{2}\left(\alpha_1^2 + \alpha_2^2\right) + H(\alpha_1 + \alpha_2), \tag{2}$$

in which P is a fixed cost, $\frac{K}{2}\left(\alpha_1^2 + \alpha_2^2\right)$ is the sum of the plant costs, and $H(\alpha_1 + \alpha_2) < 0$ [8] is the saving gained thanks to the cooperation in investment decision. Current literature on exchange of energy between prosumers focuses on a context where exchange occurs only virtually (P2P Cloud), therefore we assume that P represents the sunk cost the prosumers have to pay to access to the P2P energy community through the SG. The investment cost function $I(\alpha_i, \alpha_j)$ is assumed to be increasing and convex [9]

Assumption 5: energy selling price. Prosumers receive information on selling prices at the beginning of each time interval dt and make decisions on how much of the produced energy to self consume and how much to sell. There is only one hourly local spot market in which prosumers observe selling prices and instantaneously decide either to sell the production or not. Each prosumer's aim is to minimize energy costs, thus investment decision depends on their energy demands and the ratio between the buying and selling prices of energy. We define with dv_t the price increment overtime of the stochastic energy selling price (v_t) which follows an Arithmetic Brownian Motion (ABM)[10]

$$dv_t = \theta dt + \sigma dW_t, \tag{3}$$

where dW_t is the increment of Wiener's process (normally distributed with zero mean and variance dt). The price v_t and its expected value at time $t = \tau$ are respectively

$$v_t = v_{t_0} + \theta(t - t_0) + \sigma(W_t - W_{t_0}), \tag{4}$$

$$\mathbb{E}_{t_0}[v_t] = v_{t_0} + \theta(t - t_0), \tag{5}$$

in which θ is the (constant) increment in the energy price over time (measured in monetary units), and σ is the instantaneous standard deviation of dv_t.

Assumption 6: price of the exchanged energy. Under the assumption of exchange possibility and cooperative investment, prosumers require to agree on the price of the energy exchanged (that we call z). It is more than reasonable to assume that such agreement is reached at the same moment in which the investment decision is jointly undertaken ($t = \tau$) and that prosumers decide to set this price equal to the one paid by the TSO for the energy the prosumers

[8] MIT (2015) states that "economies of scale play a vital role in determining the optimum size of a concentrated solar power plant" and that "interconnecting load clusters makes it possible to exploit economies of scale in generation"

[9] Sunk costs are assumed to be quadratic, for the sake of simplification. None of the results are altered if investment costs are represented by a more general formulation: $I(\alpha_1, \alpha_2) = K\left(\alpha_1^\delta + \alpha_2^\delta\right)$ where $\delta > 1$

[10] There is a wide literature on electricity prices. The most relevant for our work are Gianfreda and Grossi (2012), and Fanone et al. (2013), whereas Alexander et al. (2012) refer to the use of ABM stochastic process in real options theory.

sell to the national grid (v_t) [11].
Assumption 7: plant maintenance cost. The plant maintenance cost is proportional to its capacity: $a\alpha_i$[12].

2.2 Prosumers net operative cost function under exchange scenario

The instantaneous net operative cost function of each prosumer i, is

$$\begin{aligned} C_i\left(\xi_i,\gamma_i,\alpha_i\right) =& a\alpha_i + c\left[1-\xi_i\alpha_i-\gamma_i\left(1-\xi_j\right)\alpha_j\right]+z\gamma_i\left(1-\xi_j\right)\alpha_j \\ &- z\gamma_j\left(1-\xi_i\right)\alpha_i - v_t\left(1-\xi_j\right)\left(1-\xi_i\right)\alpha_i, \end{aligned} \tag{6}$$

where $a\alpha_i$ is the plant maintenance cost, $c\left[1-\xi_i\alpha_i-\gamma_i\left(1-\xi_j\right)\alpha_j\right]$ is the cost paid by the prosumer i to buy energy from the national grid, $z\gamma_i\left(1-\xi_j\right)\alpha_j$ is the cost of energy from the other prosumer (exchange). Since $(1-\xi_i\alpha_i)$ represents the amount of energy produced by the PV plant and not self consumed, each prosumer can sell it either to the national grid at price v_t or to the other prosumer at price z. The revenue from the energy sold in exchange to prosumer j is $z\gamma_j\left(1-\xi_i\right)\alpha_i$, whereas the revenue from selling to the national grid is $v_t\left(1-\xi_j\right)\left(1-\xi_i\right)\alpha_i$. In assumption 6 we set $z=v_t$, and equation (6) becomes

$$C_i\left(\xi_i,\gamma_i,\alpha_i\right) = a\alpha_i + c - v_t\alpha_i + \left(v_t-c\right)\xi_i\alpha_i + \left(v_t-c\right)\gamma_i(1-\xi_j)\alpha_j. \tag{7}$$

The net operative cost function $C_i\left(\xi_i,\gamma_i,\alpha_i\right)$ is decreasing in ξ_i and γ_i only if $v_t<c$,[13] i.e. when the price paid by the TSO is lower than the one each prosumer pays to buy energy from it. This implies that self consumption and exchange possibility minimize energy costs only under the first scenario, leading to the following optimal self consumption and exchange behavior choices:

$$\begin{cases} v_t<c & \rightarrow \xi_i\in\left(0,\bar{\xi_i}\right],\gamma_i\in\left(0,\bar{\gamma_i}\right], \\ v_t\geq c & \rightarrow \xi_i,\gamma_i=0, \end{cases} \tag{8}$$

and equation (7) becomes

$$C_i\left(\xi_i,\gamma_i,\alpha_i\right) = a\alpha_i + c - v_t\alpha_i - \left[\xi_i\alpha_i + \left(1-\xi_j\right)\alpha_j\gamma_i\right]\left(c-v_t\right)\mathbb{I}_{v<c}, \tag{9}$$

[11] Zafar et al. (2018) underline the importance of a negotiation process to determine the price of the exchanged energy, whereas Ilic et al. (2012) mention the example of EU project NOBEL where the price is determined in a stock exchange market structure. Alam et al. (2013) set the Microgrid energy price in range from 0 to the grid energy price level, whereas Mengelkamp et al. (2017) state that local prices should converge towards the grid prices under perfect information.

[12] Here, a represents the maintenance cost per unit of installed capacity and can be considered as the marginal cost of internal production. Since solar radiations represents the production input and are for free, the marginal production costs for the PV power plants may considered negligible, thus a will be set at nil (Bertolini et al., 2018, Tveten et al., 2013, Mercure and Salas, 2012).

[13] $\frac{\partial C_i(\xi_i,\gamma_i,\alpha_i)}{\partial\xi_i}=\left(v_t-c\right)\alpha_i$ and $\frac{\partial C_i(\xi_i,\gamma_i,\alpha_i)}{\partial\gamma_i}=\left(v_t-c\right)\left(1-\xi_j\right)\alpha_j$

in which $\mathbb{I}_\varepsilon$ is the indicator function of the event ε, whose value is 1 is the event occurs, and 0 otherwise.

To assure that the investment always minimizes net operative cost once the optimal timing $t = \tau$ is reached, the following conditions must hold simultaneously[14]

$$\begin{cases} C_i(\xi_i, \gamma_i, \alpha_i) < c, \\ C_i(\xi_i, \gamma_i, \alpha_i) < C_i(\xi_i, 0, \alpha_i), & \text{iff} \quad v_t < c \\ C_i(\xi_i, \gamma_i, \alpha_i) \geq C_i(0, 0, \alpha_i), & \text{iff} \quad v_t \geq c \end{cases} \tag{10}$$

First inequality is always satisfied iff $v_t > 0$ and $\xi_i \neq \gamma_i (1 - \xi_j) \frac{\alpha_j}{\alpha_i}$, whereas the second, which is always verified, assures that the possibility to exchange energy minimizes costs when self consumption occurs, thus when $v_t < c$. If instead $v_t \geq c$ net cost minimization is assured by the absence of self consumption and exchange ($\xi_i, \gamma_i = 0$).

2.3 Optimization

The optimization problem described by equation (11) is set to minimize total net operative cost under the assumption of a cooperative investment decision between prosumers with the aim to identify the optimal size of the PV plant of each prosumer (α_i^*) and the price threshold that triggers the investment decision (v_τ).

Before the investment (at time τ), each prosumer pays a constant cost c for buying energy. When the investment is undertaken, the prosumer pays the cost $I(\alpha_1, \alpha_2)$, and after that moment, it pays the cost C_i as defined in (7).

Thus, the cost minimizing problem for the prosumers together can be written as follows:

$$\min_{\alpha_1, \alpha_2, \tau} \mathbb{E}\{\mathcal{C}(\dots)\} \quad \text{where} \tag{11}$$

$$\begin{aligned} \mathcal{C}(\dots) = &\int_0^\tau c e^{-rt} dt + \int_\tau^\infty C_1(\xi_i, \gamma_i, \alpha_i) e^{-rt} dt \\ &+ \int_0^\tau c e^{-rt} dt + \int_\tau^\infty C_2(\xi_i, \gamma_i, \alpha_i) e^{-rt} dt \\ &+ I(\alpha_1, \alpha_2) e^{-r\tau}. \end{aligned}$$

After plugging the previous equation into the problem, it becomes

$$\begin{aligned} \min_{\alpha_1, \alpha_2, \tau} &\left(H(\alpha_1 + \alpha_2) + \frac{K}{2}\left(\alpha_1^2 + \alpha_2^2\right) + P \right) \mathbb{E}_0 \left[\; e^{-r\tau} \; \right] \\ &\frac{2c}{r} + a(\alpha_1 + \alpha_2) \mathbb{E}_0 \left[\int_\tau^\infty e^{-rt} dt \right] - (\alpha_1 + \alpha_2) \mathbb{E}_0 \left[\int_\tau^\infty v_t e^{-rt} dt \right] \\ &- \left((\xi_2 + (1 - \xi_2)\gamma_1)\alpha_2 + (\xi_1 + (1 - \xi_1)\gamma_2)\alpha_1 \right) \mathbb{E}_0 \left[\; \textstyle\int_\tau^\infty (c - v_t) \mathbb{I}_{v_t < c} e^{-rt} dt \; \right], \end{aligned} \tag{12}$$

[14] See Appendix A

where $\mathbb{E}_0\left[e^{-r\tau}\right] = e^{-\beta^* \frac{v_\tau - v_0}{\sigma}}$ and v_0 is the initial price, v_τ is the price threshold that triggers the investment, and $\beta^* = -\frac{\theta}{\sigma} + \sqrt{\left(\frac{\theta}{\sigma}\right)^2 + 2r}$ is obtained through the Martingale approach. The other expected values are

$$\mathbb{E}_0\left[\int_\tau^\infty e^{-rt}dt\right] = \frac{1}{r}\mathbb{E}_0\left[e^{-r\tau}\right], \tag{13}$$

$$\mathbb{E}_0\left[\int_\tau^\infty v_t e^{-rt}dt\right] = \frac{1}{r}\mathbb{E}_0\left[e^{-r\tau}v_\tau\right] + \frac{\theta}{r^2}\mathbb{E}_0\left[e^{-r\tau}\right], \tag{14}$$

$$\mathbb{E}_0\left[e^{-r\tau}v_\tau\right] = v_\tau e^{-\beta^* \frac{v_\tau - v_0}{\sigma}} = v_\tau \mathbb{E}_0\left[e^{-r\tau}\right], \tag{15}$$

and the expected value with the option is obtained according to Dixit et al. (1994)

$$\begin{aligned} &\mathbb{E}_0\left[\ \int_\tau^\infty (c - v_t)\,\mathbb{I}_{v_t<c}e^{-rt}dt\ \right] \\ &= \left(\left(Ae^{\beta_1 v_\tau} - \frac{v_\tau}{r} + \frac{c}{r} - \frac{\theta}{r^2}\right)\mathbb{I}_{v_\tau<c} + Be^{\beta_2 v_\tau}\mathbb{I}_{v_\tau\geq c}\right)\mathbb{E}_0\left[e^{-r\tau}\right]. \end{aligned} \tag{16}$$

The optimal capacity and price threshold for each prosumer are obtained by solving numerically the following systems of first order conditions in the two different cases, for $v_\tau < c$ and $v_\tau > c$.

If $v_\tau < c$, self consumption minimizes the prosumer net cost and the optimal capacity and price threshold that triggers the investment are obtained by solving numerically the following:

$$(\alpha_1^*, \alpha_2^*, v^*)_{v_\tau<c} : \begin{cases} 0 = & H + K\alpha_1^* + \frac{a}{r} - \frac{v^*}{r} - \frac{\theta}{r^2} - (\xi_1 + (1-\xi_1)\gamma_2)\left(Ae^{\beta_1 v^*} - \frac{v^*}{r} + \frac{c}{r} - \frac{\theta}{r^2}\right) \\ 0 = & H + K\alpha_2^* + \frac{a}{r} - \frac{v^*}{r} - \frac{\theta}{r^2} - (\xi_2 + (1-\xi_2)\gamma_1)\left(Ae^{\beta_1 v^*} - \frac{v^*}{r} + \frac{c}{r} - \frac{\theta}{r^2}\right) \\ 0 = & -\beta_1\left(P + H(\alpha_1+\alpha_2) + \frac{K}{2}\left(\alpha_1^2 + \alpha_2^2\right)\right) - \frac{a}{r}(\alpha_1+\alpha_2)\beta_1 \\ & -\frac{1}{r}(\alpha_1+\alpha_2)(1 - v^*\beta_1) + \frac{\theta}{r^2}(\alpha_1+\alpha_2)\beta_1 \\ & +((\xi_2 + (1-\xi_2)\gamma_1)\alpha_2 + (\xi_1 + (1-\xi_1)\gamma_2)\alpha_1)\left(Ae^{\beta_1 v^*} - \frac{v^*}{r} + \frac{c}{r} - \frac{\theta}{r^2}\right)\beta_1 \\ & -((\xi_2 + (1-\xi_2)\gamma_1)\alpha_2 + (\xi_1 + (1-\xi_1)\gamma_2)\alpha_1)\left(\beta_1 Ae^{\beta_1 v^*} - \frac{1}{r}\right). \end{cases} \tag{17}$$

Instead, when $v_\tau \geq c$, the prosumers minimize net operative costs by selling and buying energy to and from the national grid, and the system of first order conditions is as follows:

$$(\alpha_1^*, \alpha_2^*, v^*)_{v_\tau\geq c} : \begin{cases} 0 = & H + K\alpha_1^* + \frac{a}{r} - \frac{v^*}{r} - \frac{\theta}{r^2} - (\xi_1 + (1-\xi_1)\gamma_2)Be^{\beta_2 v^*} \\ 0 = & H + K\alpha_2^* + \frac{a}{r} - \frac{v^*}{r} - \frac{\theta}{r^2} - (\xi_2 + (1-\xi_2)\gamma_1)Be^{\beta_2 v^*} \\ 0 = & -\beta_1\left(P + H(\alpha_1+\alpha_2) + \frac{K}{2}\left(\alpha_1^2 + \alpha_2^2\right)\right) + \frac{a}{r}(\alpha_1+\alpha_2)\beta_1 \\ & -\frac{1}{r}(\alpha_1+\alpha_2)(1 - v^*\beta_1) + \frac{\theta}{r^2}(\alpha_1+\alpha_2)\beta_1 \\ & +((\xi_2 + (1-\xi_2)\gamma_1)\alpha_2 + (\xi_1 + (1-\xi_1)\gamma_2)\alpha_1)\beta_1 Be^{\beta_2 v^*} \\ & -((\xi_2 + (1-\xi_2)\gamma_1)\alpha_2 + (\xi_1 + (1-\xi_1)\gamma_2)\alpha_1)\beta_2 Be^{\beta_2 v^*}. \end{cases} \tag{18}$$

3 Calibration of the model

Model calibration focuses on the northern Italy electricity market over the time interval from 2012 to 2018. Parameters (θ, σ) of the price paid to the prosumers by the TSO for the energy sold to the national grid (v_t) are obtained with the method of moments using Italian Zonal prices (geographical prices). The dataset is built starting from hourly prices of the Single National Price (PUN)[15] for northern Italy available on the website of the Italian TSO GME (Gestore Mercati Energetici)[16] and taking into account the daily time interval from 8 a.m to 7. p.m as reference of the PV plant operating time. Average monthly prices are computed, seasonally adjusted and non-stationarity assumption is verified with Dickey Fuller test[17]. The value of the price v_t at the beginning of the time period $(v_{t=0})$ is 87.13 euro/Mwh, the minimum $\left(v_t^{min}\right)$ is 32.26 euro/Mwh and the maximum (v_t^{max}) is 103.63 euro/Mwh. The annual drift and standard deviation of the price v_t yields respectively $\theta = -3.19$ and $\sigma = 34.30$.
The price paid by the prosumers to buy energy from the national grid (c) is assumed to be constant over the time interval and set equal to 154.00 euro/Mwh, that is the maximum value of the electricity price paid by household consumers in the European Market[18]. As per assumption 6, the price agreed between prosumers for the exchanged energy z is set equal to v_t.
With reference to the PV plant investment cost $(I(\alpha_1, \alpha_2))$, the parameter K is computed using the same approach described by Bertolini et al. (2018)[19]. The average plant life time interval is 25 years, thus T is set equal to 25 [20], whereas the levelized cost of energy $(LCOE)$ for PV technology equal to 100 euro/Mwh [21]. The discount rate r is defined as an average of the values used in Bertolini et al. (2018) and set equal to the 0.05. The parameter H of the investment cost function represents the cost saving gained by the prosumers from their decision to undertake the investment cooperatively. On the basis of MIT (2015) H it is set equal to $-0.15K$[22], whereas the sunk cost to access to the Smart Grid

[15] PUN: Prezzo Unico Nazionale / Unique National Price.

[16] `https://www.mercatoelettrico.org/en/download/DatiStorici.aspx`

[17] Augmented Dickey-Fuller Test is performed in R with adf.test command, where the alternative hypothesis is stationarity. Test result is -2.0623 and p-value is equal to 0.5503. Thus we fail to reject the null hypothesis.

[18] Eurostat - Energy Statistics, Electricity prices for household consumers - bi-annual data (from 2007 onwards) [nrg_pc_204]. The data are in in Euro currency, refer to an annual consumption between 2 500 and 5 000 kWh (Band-DC, Medium), excluding taxes and levies.

[19]
$$K = 2\frac{LCOE}{r}\left(1 - e^{-rT}\right)$$
.

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

[21] IEA (2018) identifies an average value of the solar PV levelized cost of electricity in 2017 equal to 100 euro/Mwh

[22] MIT (2015) analyses the decline of PV system prices in US from 2004 to 2014 at residential and commercial level. A 50% decline in the residential prices and 70% in utility prices was assessed. “Prices for commercial systems showed a similar decline, with the absolute price per watt tending to lie 10%–15% below the residential average during this period”. We use this variation as a proxy of the cost saving prosumers can gain from cooperation. Thus we set $H = -0.15K$

P is set equal to $0.1K$[23] and the PV plant maintenance cost a is set equal to 0. Prosumers' self consumption behavior is described by parameter $\xi_i \in [0; \bar{\xi_i}]$, where $\bar{\xi_i} = 0.45$[24] Finally with reference to energy exchange P2P behavior, represented by $\gamma_i \in [0; \bar{\gamma_i}]$ and since prosumers are assumed to be asymmetric in load curves, $\bar{\gamma_i}$ is set equal to 0.15[25].

Table 3.1 provides a brief on all parameters used for model calibration.

[23]With reference to Italy, we set parameter P as a share (0.1) of the capital cost K, as an average of two possible fees coming from 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.

[24]Kästel and Gilroy-Scott (2015), Ciabattoni et al. (2014)

[25]Sousa et al. (2019), Zhang et al. (2018).

Parameter	*Description*	*Value*	*Source/Reference*
θ	drift	-3.19	Calibrated on PUN, TSO GME
σ	volatility	34.30	Calibrated on PUN TSO GME
v_0	price v_t at the beginning of the time period	87.13	PUN, TSO GME
c	cost to buy energy from the national grid	154.00	Eurostat
T	PV plant lifetime (years)	25	Branker et al. (2011), Kästel and Gilroy-Scott (2015)
r	discount rate	0.05	Bertolini et al. (2018)
$LCOE$	levelized cost of electricity for PV plants euro	100.00	IEA (2018)
K	PV plant cost of capital	2853.98	Computed, Bertolini et al. (2018)
a	PV plant maintenance cost	0	Bertolini et al. (2018),Mercure and Salas (2012), Tveten et al. (2013)
H	prosumers gain from cooperation	$-0.15K$	Computed, MIT (2015)
P	cost to access to virtual exchange platform	$0.10K$	Computed, fonte da inserire
ξ_i	prosumers' self consumption parameter	0.30	Kästel and Gilroy-Scott (2015) Ciabattoni et al. (2014)
γ_i	prosumers' exchange parameter	0.10	Sousa et al. (2019), Zhang et al. (2018)

Table 3.1: Parameters

4 Main results and comparative statics

This section is devoted to the main results and comparative statics. We define the following four scenarios: $E(v_\tau < c)$ and $E(v_\tau > c)$ refer to the cases with exchange possibility (E, Exchange) and where v_τ is lower and higher than c respectively, whereas $NE(v_\tau < c)$ and $NE(v_\tau > c)$ refer to the cases in which exchange possibility is yet to be introduced (NE, No Exchange). The NE cases are obtained by setting $\gamma_i = 0$.
Numerical solution for $E(v_\tau < c)$ and $E(v_\tau > c)$ are obtained from equations (17) and (18), whereas $NE(v_\tau < c)$ and $NE(v_\tau > c)$ from equations (C.6) and (C.7) in Appendix C. In the following tables and figures, we show and comment the four scenarios. We present the optimal size α_i^* and the selling price v^* which triggers investments[26]. Furthermore, for each case we also show the optimal investment cost (I_i^*) for each prosumer and the overall net operative cost $(\mathbb{E}_0[OC_i^*])$ [27]. In case of multiple viable thresholds we will choose the scenario with the lowest $\mathbb{E}_0[OC_i^*]$.
In Table 4.1, we present the benchmark case, calculated by using the parameters of Table 3.1.

Scenario	α_i^*	v^*	I_i^*	$\mathbb{E}_0[OC_i^*]$
$E(v_\tau > c)$	1.635163	259.119	3258.118	2247.551
$E(v_\tau < c)$	**0.948976**	**139.987**	1021.530	**1951.837**
$NE(v_\tau > c)$	-	-	-	-
$NE(v_\tau < c)$	0.699665	131.071	698.557	2267.01

Table 4.1: Optimal capacities, price thresholds, investment costs and net operative costs, with $\xi_i = 0.30$, $\gamma_i = 0.10$, $c = 154$, $v_0 = 87.13$, $\theta = -3.19$, $\sigma = 34.30$, $r = 0.05$, $T = 25$, $LCOE = 100$, $P = 0.10K$, $H = -0.15K$

Table 4.1 shows three viable solutions of v^*. Two of them are for the scenario E and one for scenario NE. See also Figure 4.1 below, showing optimal triggers, v_t and c.

[26] Optimal capacity is expressed in Mwh, whereas price threshold, optimal investment and overall net operative cost in euro/Mwh.

[27] where $I_i^* \equiv \frac{I(\alpha_1^*;\alpha_2^*)}{2}$ and $\mathbb{E}_0[OC_i^*] \equiv \mathbb{E}_0\left[\int_0^\tau ce^{-rt}dt + \int_\tau^\infty C_i^*(\dots)e^{-rt}dt\right]$

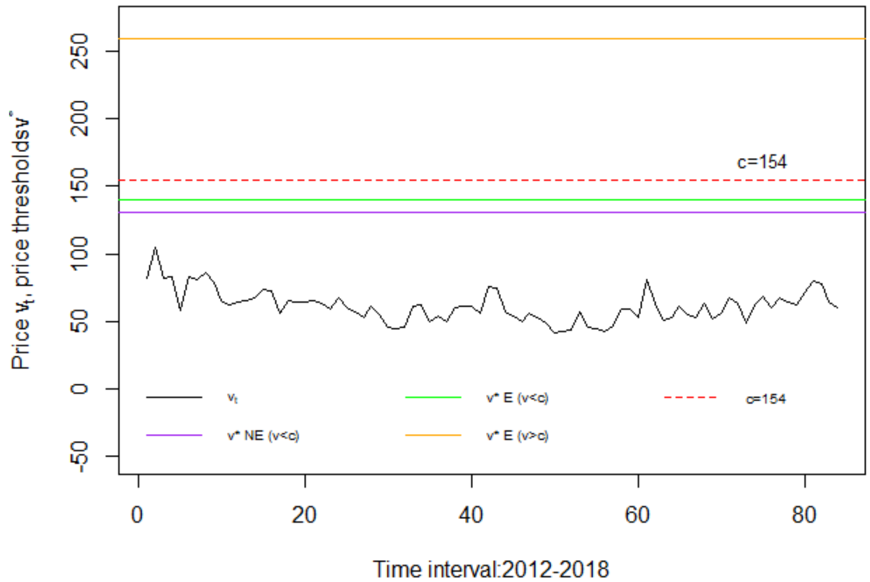

Figure 4.1: Northern Italy price and price thresholds comparison, with with $\xi_i = 0.30$, $\gamma_i = 0.10$, $c = 154$, $v_0 = 87.13$, $\theta = -3.19$, $\sigma = 34.30$, $r = 0.05$, $T = 25$, $LCOE = 100$, $P = 0.10K$, $H = -0.15K$

In the benchmark, the lowest net operative cost $\mathbb{E}_0 [OC_i^*]$ is given by scenario E where the value of energy exchanged is always positive and it makes the agents better off. Furthermore, the possibility of selling energy between agents (i.e., the option to switch) encourages prosumers to invest in larger plants when compared with plants sized according to scenario NE.
Table 4.2 shows, for the E scenarios, the comparative statics of a change of ξ_i and γ_i parameters. We move from "sales-oriented profile" agents, characterized by low values of both ξ_i and γ_i, to "exchange-oriented profile" agents with higher values of ξ_i and γ_i. Higher values of ξ_i and γ_i represent the case in which the load / demand curves of the agents allow them to exchange and self consume a higher share of their production. A "sales-oriented profile" agent would like to invest for selling energy to the national grid, gaining from the difference between v_τ and c in sales. This is coherent with the result in Table 4.2 where the viable scenario is $E\,(v_t > c)$. On the contrary, an "exchange-oriented profile" agent invests for reducing the cost of energy by increasing self-consumption and exchange. This is coherent with the result in Table 4.2 that the viable scenario is $E\,(v_t < c)$.
Moreover, comparing the net operative cost $\mathbb{E}_0 [OC_i^*]$ between the scenario

where $E(v_\tau < c)$ and the scenario $E(v_\tau > c)$, we observe that the cost related to $E(v_\tau < c)$ is always smaller regardless of the shape of the load / demand curve. And this is true although the optimal size of the plant is reduced with increasing ξ_i and γ_i. This is to say that "exchange-oriented profile" agents are able to use more efficiently their PV plants, i.e. to invest earlier and with a lower optimal size of the plant. We can interpret the difference between the net operative cost $\mathbb{E}_0\left[OC_i^*\right]$ in the case where $\xi_i = 0.10$ and $\gamma_i = 0.05$, and the net operative cost in the case $\xi_i = 0.35$ and $\gamma_i = 0.15$, as the maximum amount that each agent would be willing to pay for a technology able to increase self-consumption and exchange (i.e. home automation).

Parameters	Scenario	α_i^*	v^*	I_i^*	$\mathbb{E}_0\left[OC_i^*\right]$
$\xi_i = 0.10$; $\gamma_i = 0.05$	$E\left(v_\tau > c\right)$	1.408054	235.698	2369.090	2269.625
	$E\left(v_\tau < c\right)$	-	-	-	-
$\xi_i = 0.30$; $\gamma_i = 0.10$	$E\left(v_\tau > c\right)$	1.635163	259.119	3258.118	2247.551
	$E\left(v_\tau < c\right)$	0.948976	139.987	1021.530	1951.837
$\xi_i = 0.35$; $\gamma_i = 0.15$	$E\left(v_\tau > c\right)$	1.701074	265.964	3543.692	2248.722
	$E\left(v_\tau < c\right)$	**0.847737**	**106.233**	805.303	**1745.941**

Table 4.2: Optimal capacities and price thresholds as a function of ξ_i and γ_i with $\mathbf{\xi_i = 0.30}$, $\mathbf{\gamma_i = 0.10}$, $c = 154$, $v_0 = 87.13$, $\theta = -3.19$, $\sigma = 34.30$, $r = 0.05$, $T = 25$, $LCOE = 100$, $P = 0.10K$, $H = -0.15K$

Table 4.3 shows the comparative statics with respect σ. Three comments are in order for this table: 1) in line with standard results in the Real Option literature on investment timing flexibility, the greater the volatility of prices, the greater the option value to defer the investment and, in turn, the greater the investment value (see Bar-Ilan and Strange, 1999; Dangl, 1999; Hagspiel et al., 2016); 2) with high volatility the PV plant is built for selling. Indeed, the viable scenario is $E\left(v_\tau > c\right)$ for $\sigma = 40$, whereas is $E\left(v_\tau < c\right)$ for $\sigma = 30$ and 20 (see Figure 4.2); 3) there is a positive relation between α_i^* and v^*. In order to invest in a larger plant, prosumers wait longer, to be profitable. When σ is high, the option to delay prevails over the option to exchange and each agent delays to make the sale convenient. In other words, if a policymaker would like to push towards energy community, it should try to stabilize the energy prices, thus reducing σ.

Parameters	Scenario	α_i^*	v^*	I_i^*	$\mathbb{E}_0\left[OC_i^*\right]$
$\sigma = 40$	$E\left(v_\tau > c\right)$	**1.863268**	**292.383**	4299.221	**1945.291**
	$E\left(v_\tau < c\right)$	-	-	-	-
	$NE\left(v_\tau > c\right)$	0.890449	162.066	1131.461	2022.237
	$NE\left(v_\tau < c\right)$	-	-	-	-
$\sigma = 30$	$E\left(v_\tau > c\right)$	1.471143	234.923	2601.290	2445.350
	$E\left(v_\tau < c\right)$	**0.792776**	**111.669**	700.1702	**2065.294**
	$NE\left(v_\tau > c\right)$	-	-	-	-
	$NE\left(v_\tau < c\right)$	0.569402	108.798	462.657	2406.617
$\sigma = 20$	$E\left(v_\tau > c\right)$	1.1337197	183.533	1491.496	2812.596
	$E\left(v_\tau < c\right)$	**0.535413**	**60.139**	322.562	**1901.717**
	$NE\left(v_\tau > c\right)$	-	-	-	-
	$NE\left(v_\tau < c\right)$	0.313163	61.265	139.9473	2535.985

Table 4.3: Optimal capacities and price thresholds as a function of σ with $\xi_i = 0.30$, $\gamma_i = 0.10$, $c = 154$, $v_0 = 87.13$, $\theta = -3.19$, $\sigma = \mathbf{34.30}$, $r = 0.05$, $T = 25$, $LCOE = 100$, $P = 0.10K$, $H = -0.15K$

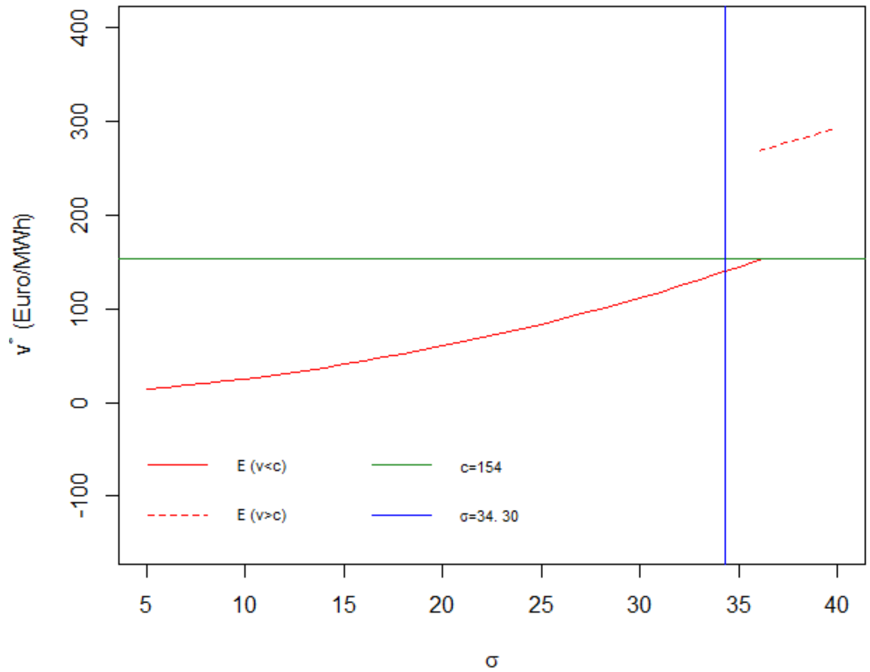

Figure 4.2: Price thresholds as a function of σ, with $\xi_i = 0.30$, $\gamma_i = 0.10$, $c = 154$, $v_0 = 87.13$, $\theta = -3.19$, $\sigma = \mathbf{34.30}$, $r = 0.05$, $T = 25$, $LCOE = 100$, $P = 0.10K$, $H = -0.15K$.

Table 4.4 and Table 4.5 show comparative statics with respect different values for $LCOE$ (110 and 80) and plant lifetime T (20 and 30). An increase in $LCOE$ implies an increase in investment timing and a reduction in plant size. Intuitively, higher $LCOE$ implies higher investment costs which, in turn, cause a generalized investment delay. This delay can be reduced by reducing the plant size. A change of plant lifetime T generates a similar effect: when T increases, ceteris paribus, plant size decreases and the selling price triggering the investment increases (i.e., the agent invests later).

Parameters	Scenario	α_i^*	v^*	I_i^*	$\mathbb{E}_0\left[OC_i^*\right]$	K
$LCOE =$ 110	$E\left(v_\tau > c\right)$	1.498441	258.816	2975.807	2315.272	3139.380
	$E\left(v_\tau < c\right)$	**0.882003**	**141.184**	962.736	2038.753	3139.38
	$NE\left(v_\tau > c\right)$	-	-	-	-	-
	$NE\left(v_\tau < c\right)$	0.636059	131.071	635.052	2340.926	3139.38
$LCOE =$ 80	$E\left(v_\tau > c\right)$	2.013789	260.065	4054.034	2062.670	2283.18
	$E\left(v_\tau < c\right)$	**1.139501**	**138.566**	1206.220	1714.136	2283.18
	$NE\left(v_\tau > c\right)$	-	-	-	-	-
	$NE\left(v_\tau < c\right)$	0.874582	131.071	873.197	2063.774	2283.18

Table 4.4: Optimal capacities and price thresholds as a function of $LCOE$ with $\xi_i = 0.30$, $\gamma_i = 0.10$, $c = 154$, $v_0 = 87.13$, $\theta = -3.19$, $\sigma = 34.30$, $r = 0.05$, $T = 25$, $\mathbf{LCOE = 100}$, $P = 0.10K$, $H = -0.15K$

Parameters	Scenario	α_i^*	v^*	I_i^*	$\mathbb{E}_0\left[OC_i^*\right]$
$T = 30$	$E\left(v_\tau > c\right)$	1.512445	258.845	3004.556	2308.303
	$E\left(v_\tau < c\right)$	**0.888809**	**141.036**	968.507	**2029.809**
	$NE\left(v_\tau > c\right)$	-	-	-	-
	$NE\left(v_\tau < c\right)$	0.642589	131.071	641.571	2333.340
$T = 20$	$E\left(v_\tau > c\right)$	1.829729	259.601	3665.021	2152.153
	$E\left(v_\tau < c\right)$	**1.046068**	**139.004**	1113.085	**1829.298**
	$NE\left(v_\tau > c\right)$	-	-	-	-
	$NE\left(v_\tau < c\right)$	0.789735	131.071	788.484	2162.362

Table 4.5: Optimal capacities and price thresholds as a function of T with $\xi_i = 0.30$, $\gamma_i = 0.10$, $c = 154$, $v_0 = 87.13$, $\theta = -3.19$, $\sigma = 34.30$, $r = 0.05$, $\mathbf{T = 25}$, $LCOE = 100$, $P = 0.10K$, $H = -0.15K$

5 Conclusions

In this work, we model two prosumers' investment decisions in a PV plant connected to the SG. Each prosumer can: a) self-consume its energy production; b) exchange energy with national grid and/or c) exchange energy with the other agent . According to the characteristics of the each load/demand factor, we distinguish between "sales-oriented profiles" that would like to invest for selling energy to the national grid and "exchange-oriented profiles" that invest for reducing the cost of energy by increasing self-consumption and exchange. Our findings show that: 1) in the benchmark case, value of exchange is always positive; 2) the option value to defer investment is positive; 3) the possibility of selling energy between agents encourages investment in larger plants, compared with the cases with self-consumption and only exchange with national grid; 4) the "exchange-oriented profile" agents invest earlier and with a lower optimal size of the plant; 5) there is a positive relation between plant optimal size and optimal investment timing (i.e., the greater the plant optimal size, the greater the investment deferral). About the volatility effect, on one hand it is perfectly in line, on the other hand it shows an interesting results. Indeed the greater the volatility, the higher the option value to defer and, in turn, the greater the investment value. At the same time, with high volatility, the PV plant is built for selling and not for exchange purpose. Thus, an interesting policy implication is that if policymakers would like to push energy community diffusion, they should stabilize the energy prices volatility. Lastly, two possible extensions of our research could be: 1) relax the assumption on the load factors studying different possibilities with totally asymmetric prosumers and calculating which profile is more viable, 2) applying our approach to the PV plant disposal problem in order to understand policy implications related to this topic.

A Appendix: cost minimization conditions

In order to assure that once the optimal timing $t = \tau$ is reached the investment always minimizes net operative cost, the following conditions must hold simultaneously

$$\begin{cases} C_i(\xi_i, \gamma_i, \alpha_i) < c, \\ C_i(\xi_i, \gamma_i, \alpha_i) < C_i(\xi_i, 0, \alpha_i) & \text{iff} \quad v_t < c, \\ C_i(\xi_i, \gamma_i, \alpha_i) \geq C_i(0, 0, \alpha_i) & \text{iff} \quad v_t \geq c. \end{cases} \tag{A.1}$$

First condition assures that once the threshold is reached the investment always minimizes prosumers' energy costs

$$\begin{aligned} C_i(\xi_i, \gamma_i, \alpha_i) &< c \\ a\alpha_i + c - v_t\alpha_i - [\xi_i\alpha_i + (1-\xi_j)\alpha_j\gamma_i](c - v_t)\mathbb{I}_{v<c} &< c \\ a &< v_t + \left[\xi_i + (1-\xi_j)\frac{\alpha_j}{\alpha_i}\gamma_i\right](c - v_t)\mathbb{I}_{v<c}, \end{aligned} \tag{A.2}$$

which can be rewritten as follows

$$\begin{cases} a < v_t + \left[\xi_i + \gamma_i(1-\xi_j)\frac{\alpha_j}{\alpha_i}\right](c - v_t) & v_t < c, \\ a < v_t & v_t \geq c. \end{cases} \tag{A.3}$$

Since a represents the PV plant maintenance cost and we assume it to be nil ($a = 0$), the previous system can be rewritten as follows

$$\begin{cases} v_t > -\left[\xi_i + \gamma_i(1-\xi_j)\frac{\alpha_j}{\alpha_i}\right](c - v_t), & v_t < c \\ v_t > 0, & v_t \geq c \end{cases} \tag{A.4}$$

and if $v_t < c$, the RHS is always negative, first inequality is always satisfied iff $v_t > 0$ and $\xi_i \neq \gamma_i(1-\xi_j)\frac{\alpha_j}{\alpha_i}$[28]. *Second condition* assures that exchange possibility introduction minimizes prosumers' energy costs and it is satisfied only if self consumption occurs, thus when $v_t < c$

$$\begin{aligned} C_i(\xi_i, \gamma_i, \alpha_i) &< C_i(\xi_i, 0, \alpha_i) \\ -(1-\xi_j)\alpha_j\gamma_i &< 0, \end{aligned} \tag{A.5}$$

if instead $v_t > c$, follows (*third condition*)

$$\begin{aligned} C_i(\xi_i, \gamma_i, \alpha_i) &\geq C_i(0, 0, \alpha_i) \\ a\alpha_i + c - v_t\alpha_i &\geq a\alpha_i + c - v_t\alpha_i, \end{aligned} \tag{A.6}$$

which is always true.

[28] if $\xi_i = \gamma_i(1-\xi_j)\frac{\alpha_j}{\alpha_i}$, $v_t = 0$ and this solution is not admissible if $v_t > c$

B Appendix: expected values computation

The following expected value

$$\mathbb{E}_0 \left[e^{-r\tau} \int_\tau^\infty e^{-r(t-\tau)} dt \right], \tag{B.1}$$

can be simplified by using the so-called tower property of (iterated) expected values. Thus, we write a new expected value inside the initial one, by using a larger filtration:

$$\mathbb{E}_0 \left[e^{-r\tau} \int_\tau^\infty e^{-r(t-\tau)} dt \right] = \mathbb{E}_0 \left[\mathbb{E}_\tau \left[e^{-r\tau} \int_\tau^\infty e^{-r(t-\tau)} dt \right] \right], \tag{B.2}$$

and since $e^{-r\tau}$ is known at time τ, this term can be collected outside the inner expected value:

$$\begin{aligned} \mathbb{E}_0 \left[e^{-r\tau} \int_\tau^\infty e^{-r(t-\tau)} dt \right] &= \mathbb{E}_0 \left[e^{-r\tau} \mathbb{E}_\tau \left[\int_\tau^\infty e^{-r(t-\tau)} dt \right] \right] \\ &= \mathbb{E}_0 \left[e^{-r\tau} \frac{1}{r} \right]. \end{aligned} \tag{B.3}$$

In the other expected value

$$\mathbb{E}_0 \left[e^{-r\tau} \int_\tau^\infty v_t e^{-r(t-\tau)} dt \right], \tag{B.4}$$

we initially use the same approach:

$$\begin{aligned} \mathbb{E}_0 \left[e^{-r\tau} \int_\tau^\infty v_t e^{-r(t-\tau)} dt \right] &= \mathbb{E}_0 \left[\mathbb{E}_\tau \left[e^{-r\tau} \int_\tau^\infty v_t e^{-r(t-\tau)} dt \right] \right] \\ &= \mathbb{E}_0 \left[e^{-r\tau} \mathbb{E}_\tau \left[\int_\tau^\infty v_t e^{-r(t-\tau)} dt \right] \right] \\ &= \mathbb{E}_0 \left[e^{-r\tau} \int_\tau^\infty \mathbb{E}_\tau \left[v_t \right] e^{-r(t-\tau)} dt \right]. \end{aligned} \tag{B.5}$$

Now we recall that, for any $t > \tau$

$$\mathbb{E}_\tau \left[v_t \right] = v_\tau + \theta \left(t - \tau \right), \tag{B.6}$$

and so

$$\begin{aligned} \mathbb{E}_0 \left[e^{-r\tau} \int_\tau^\infty v_t e^{-r(t-\tau)} dt \right] &= \mathbb{E}_0 \left[e^{-r\tau} \int_\tau^\infty \left(v_\tau + \theta \left(t - \tau \right) \right) e^{-r(t-\tau)} dt \right] \\ &= \mathbb{E}_0 \left[e^{-r\tau} v_\tau \int_\tau^\infty e^{-r(t-\tau)} dt \right] + \mathbb{E}_0 \left[\theta e^{-r\tau} \int_\tau^\infty \left(t - \tau \right) e^{-r(t-\tau)} dt \right] \\ &= \mathbb{E}_0 \left[e^{-r\tau} \frac{v_\tau}{r} \right] + \mathbb{E}_0 \left[\frac{\theta}{r^2} e^{-r\tau} \right] \\ &= \frac{1}{r} \mathbb{E}_0 \left[e^{-r\tau} v_\tau \right] + \frac{\theta}{r^2} \mathbb{E}_0 \left[e^{-r\tau} \right]. \end{aligned} \tag{B.7}$$

B.1 Expected value with the option

The expected value with the option $\mathbb{E}_0\left[\ \int_\tau^\infty (c - v_t)\,\mathbb{I}_{v_t<c} e^{-rt}dt\ \right]$ is obtained according to Dixit et al. (1994)

$$\begin{aligned}\mathbb{E}_0\left[\ \int_\tau^\infty (c - v_t)\,\mathbb{I}_{v_t<c} e^{-rt}dt\ \right] =&\mathbb{E}_0\left[e^{-r\tau}\int_\tau^\infty (c - v_t)\,\mathbb{I}_{v_t<c} e^{-r(t-\tau)}dt\right]\\ =&\mathbb{E}_0\left[\mathbb{E}_\tau\left[e^{-r\tau}\int_\tau^\infty (c - v_t)\,\mathbb{I}_{v_t<c} e^{-r(t-\tau)}dt\right]\right]\\ =&\mathbb{E}_0\left[e^{-r\tau}\mathbb{E}_\tau\left[\int_\tau^\infty (c - v_t)\,\mathbb{I}_{v_t<c} e^{-r(t-\tau)}dt\right]\right].\end{aligned} \tag{B.8}$$

Now, we set

$$V_t = \mathbb{E}_t\left[\int_t^\infty (c - v_s)\,\mathbb{I}_{v_s<c} e^{-r(s-t)}ds\right], \tag{B.9}$$

whose value V_t must solve the following PDE

$$\frac{\partial V_t}{\partial v_t}\theta + \frac{1}{2}\frac{\partial^2 V_t}{\partial v_t^2}\sigma^2 - rV_t + (c - v_t)\,\mathbb{I}_{v_t<c} = 0. \tag{B.10}$$

which can be split into two PDEs

$$\begin{cases}\frac{\partial V_t}{\partial v_t}\theta + \frac{1}{2}\frac{\partial^2 V_t}{\partial v_t^2}\sigma^2 - rV_t + c - v_t = 0 & v_t < c,\\ \frac{\partial V_t}{\partial v_t}\theta + \frac{1}{2}\frac{\partial^2 V_t}{\partial v_t^2}\sigma^2 - rV_t = 0 & v_t \geq c.\end{cases} \tag{B.11}$$

If $v_t \geq c$ the guess function is $V_t = Be^{\beta v_t}$ and the corresponding PDE can be written as

$$\beta Be^{\beta v_t}\theta + \frac{1}{2}\beta^2 Be^{\beta v_t}\sigma^2 - rBe^{\beta v_t} = 0, \tag{B.12}$$

from which

$$\beta_{1,2} = -\frac{\theta}{\sigma^2} \pm \sqrt{\left(\frac{\theta}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}}. \tag{B.13}$$

This equation has two solutions but we take only the positive one.
Thus, we set

$$V_{1,t} = Be^{\beta_1 v_t}. \tag{B.14}$$

If $v_t < c$ the guess function is

$$V_t = Ae^{\beta v_t} + Dv_t + E, \tag{B.15}$$

and when this function is plugged into the PDE we get

$$\theta\beta Ae_t^{\beta v_t} + \theta D + \frac{\sigma^2}{2}\beta^2 Ae_t^{\beta v_t} - r\left(Ae^{\beta v_t} + Dv_t + E\right) + c - v_t = 0, \tag{B.16}$$

which can be split into three equations

$$Ae_t^{\beta v_t}\left(\frac{1}{2}\beta^2\sigma^2+\theta\beta-r\right)=0, \tag{B.17}$$

$$-v_t(1+rD)=0, \tag{B.18}$$

$$\theta D-rE+c=0, \tag{B.19}$$

where the first equation is satisfied for the same value of β already presented above. In this case, instead, we take the negative value β_2.
The solution to the second equation is $D=-\frac{1}{r}$, and the solution to the last equation is $E=\frac{c}{r}-\frac{\theta}{r^2}$. Finally, the solution to the second PDE is

$$V_{2t}=Ae^{\beta_2 v_t}-\frac{1}{r}v_t+\frac{c}{r}-\frac{\theta}{r^2}. \tag{B.20}$$

Taking into account both price scenarios, the equation of V_t can be rewritten as follows

$$V_t=\begin{cases}V_{2,t}=Ae^{\beta_2 v_t}-\frac{v_t}{r}+\frac{c}{r}-\frac{\theta}{r^2}, & v_t<c,\\ V_{1,t}=Be^{\beta_1 v_t}, & v_t\geq c.\end{cases} \tag{B.21}$$

Constants A and B are obtained combining the value matching and the smooth pasting conditions. The first condition asks for $V_{1,t}$ to be the same as $V_{2,t}$ when $v_t=c$:

$$Ae^{\beta_2 c}-\frac{c}{r}+\frac{c}{r}-\frac{\theta}{r^2}=Be^{\beta_1 c}, \tag{B.22}$$

$$Ae^{\beta_2 c}-Be^{\beta_1 c}=\frac{\theta}{r^2}. \tag{B.23}$$

The second condition asks for the derivatives of V_t w.r.t. v_t are the same when $v_t=c$, i.e.

$$A\beta_2 e^{\beta_2 c}-\frac{1}{r}=B\beta_1 e^{\beta_1 c}, \tag{B.24}$$

$$A\beta_2 e^{\beta_2 c}-B\beta_1 e^{\beta_1 c}=\frac{1}{r}. \tag{B.25}$$

Combing the two conditions gives:

$$\begin{cases}Ae^{\beta_2 c}-Be^{\beta_1 c}=\frac{\theta}{r^2}\\ A\beta_2 e^{\beta_2 c}-B\beta_1 e^{\beta_1 c}=\frac{1}{r},\end{cases} \tag{B.26}$$

we find that the constants are

$$A=e^{-\beta_2 c}\frac{1}{r}\frac{1-\beta_1\frac{\theta}{r}}{\beta_2-\beta_1}, \tag{B.27}$$

$$B=e^{-\beta_1 c}\frac{1}{r}\frac{1-\beta_2\frac{\theta}{r}}{\beta_2-\beta_1}. \tag{B.28}$$

B.2 Real Option through martingale approach

Starting from $\mathbb{E}_0\left[e^{-r\tau}\right]$, given that $v_\tau - v_0 = \theta\tau + \sigma W_\tau$ and under the assumption that $W_0 = 0$, the Martingale approach exploits the property for which a process without drift is a martingale. Given a process x_t such that $dx_t = \beta x_t dW_t$

$$d\ln x_t = \left(0 + \frac{1}{x_t}0 + \frac{1}{2}\left(-\frac{1}{x_t^2}\right)\beta^2 x_t^2\right)dt + \frac{1}{x_t}\beta x_t dW_t \tag{B.29}$$

$$= -\frac{1}{2}\beta^2 dt + \beta dW_t \tag{B.30}$$

and

$$\int_0^t d\ln x_s = -\int_0^t \frac{1}{2}\beta^2 ds + \int_0^t \beta dW_s \tag{B.31}$$

$$\ln x_t - \ln x_0 = -\frac{1}{2}\beta^2 t + \beta\left(W_t - W_0\right) \tag{B.32}$$

$$\frac{x_t}{x_0} = e^{-\frac{1}{2}\beta^2 t + \beta(W_t - W_0)} \tag{B.33}$$

$$x_t = x_0 e^{-\frac{1}{2}\beta^2 t + \beta W_t} \tag{B.34}$$

and its expected value is

$$\mathbb{E}_0\left[x_t\right] = x_0 \tag{B.35}$$

$$\mathbb{E}_0\left[x_0 e^{-\frac{1}{2}\beta^2 t + \beta W_t}\right] = x_0 \tag{B.36}$$

$$\mathbb{E}_0\left[e^{-\frac{1}{2}\beta^2 t + \beta W_t}\right] = 1 \tag{B.37}$$

Considering now $W_\tau = \frac{\dot{v}_\tau - v_0 - \theta\tau}{\sigma}$[29], where v_τ represents the price threshold

$$\mathbb{E}_0\left[e^{-\frac{1}{2}\beta^2\tau + \beta\left(\frac{v_\tau - v_0 - \theta\tau}{\sigma}\right)}\right] = 1 \tag{B.38}$$

$$\mathbb{E}_0\left[e^{-\left(\frac{1}{2}\beta^2 + \beta\frac{\theta}{\sigma}\right)\tau + \beta\frac{v_\tau - v_0}{\sigma}}\right] = 1 \tag{B.39}$$

$$\mathbb{E}_0\left[e^{-\left(\frac{1}{2}\beta^2 + \beta\frac{\theta}{\sigma}\right)\tau}\right] e^{\beta\frac{v_\tau - v_0}{\sigma}} = 1 \tag{B.40}$$

$$\mathbb{E}_0\left[e^{-\left(\frac{1}{2}\beta^2 + \beta\frac{\theta}{\sigma}\right)\tau}\right] = e^{-\beta\frac{v_\tau - v_0}{\sigma}} \tag{B.41}$$

where $\beta^* = -\frac{\theta}{\sigma} \pm \sqrt{\left(\frac{\theta}{\sigma}\right)^2 + 2r}$ is the solution of the equation $\frac{1}{2}\beta^2 + \beta\frac{\theta}{\sigma} = r$. From this follows

$$\mathbb{E}_0\left[e^{-r\tau}\right] = e^{-\beta\frac{v_\tau - v_0}{\sigma}} \tag{B.42}$$

[29]obtained from $v_\tau - v_0 = \theta\tau + \sigma W_\tau$

C Appendix: model with self consumption and no exchange

This scenario is investigated in order to identify the value of flexibility provided by prosumers' cooperative investment and exchange possibility. Under this context, two additional assumptions are introduced:

- the absence of exchange with $\gamma_i = 0$
- prosumers' investment decision is no longer undertaken cooperatively.

In the latter case the investment cost function becomes

$$I(\alpha_i) = \frac{K}{2}\alpha_i^2, \tag{C.1}$$

whereas the new prosumer demand function is

$$\int_0^{24} l(s)\,ds = 1Mwh = \xi_i\alpha_i + b_i \qquad \text{with } i = 1, 2, \tag{C.2}$$
$$\text{where} \quad \xi_i \in [0,1].$$

The net operative cost function of prosumer i in absence of exchange becomes

$$C_i(\xi_i, \alpha_i) = a\alpha_i + c - v_t\alpha_i - \xi_i\alpha_i(c - v_t)\mathbb{I}_{v_t<c}, \tag{C.3}$$

and each prosumer i solves the following minimization problem

$$\min_{\alpha_i,\tau}\mathbb{E}_0\left[\int_0^\tau ce^{-rt}dt + \int_\tau^\infty C_i(\xi_i,\alpha_i)e^{-rt}dt + I(\alpha_i)e^{-r\tau}\right]. \tag{C.4}$$

Introducing the extended form of $C_i(\xi_i, \alpha_i)$ and $I(\alpha_i)$, the minimization problem can be rewritten as follows

$$\begin{aligned}\min_{\tau\in[0,\infty],\alpha\geq 0}\frac{c}{r} - \frac{\alpha_i}{r}v_\tau\mathbb{E}_0\left[e^{-r\tau}\right] + \mathbb{E}_0\left[e^{-r\tau}\right]\frac{K}{2}\alpha^2 \\ + \alpha_i\mathbb{E}_0\left[e^{-r\tau}\right]\left[\frac{a}{r} - \frac{\theta}{r^2} - \xi_i\left(Ae^{\beta_2 v_\tau} + \frac{c}{r} - \frac{\theta}{r^2} - \frac{v_\tau}{r}\right)\mathbb{I}_{v_\tau<c} - \xi_i Be^{\beta_1 v_\tau}\mathbb{I}_{v_\tau\geq c}\right].\end{aligned} \tag{C.5}$$

The optimal capacity (α_i^*) and the price threshold (v_τ) that triggers the investment for the prosumer i in absence of exchange are defined in two different cases. If $v_\tau < c$, self consumption minimizes the prosumer net operative cost and the optimal capacity and price threshold that triggers the investment are obtained solving numerically the following system:

$$(\alpha_i^*, v^*)_{v_\tau<c} : \begin{cases}\alpha_i^* - \frac{1}{K}\left[\frac{v^*}{r} - \frac{a}{r} + \frac{\theta}{r^2} + \xi_i\left(Ae^{\beta_1 v^*} + \frac{c}{r} - \frac{\theta}{r^2} - \frac{v^*}{r}\right)\right] = 0 \\ -\frac{1}{r} + \frac{v^*}{r}\beta_1 - \frac{K}{2}\alpha_i^*\beta_1 \\ \qquad - \left[\frac{a}{r} - \frac{\theta}{r^2} - \xi_i\left(Ae^{\beta_1 v^*} + \frac{c}{r} - \frac{\theta}{r^2} - \frac{v^*}{r}\right)\right]\beta_1 - \xi_i\left(\beta_1 Ae^{\beta_1 v^*} - \frac{1}{r}\right) = 0,\end{cases} \tag{C.6}$$

If $v_\tau \geq c$, the prosumer i minimizes its net operative cost by selling and buying energy to and from the national grid. Also in this case, optimal capacity and price thresholds are obtained solving numerically the following system

$$(\alpha_i^*, v^*)_{v_\tau \geq c} : \begin{cases} \alpha_i^* - \frac{1}{K}\left[\frac{v^*}{r} - \frac{a}{r} + \frac{\theta}{r^2} + \xi_i B e^{\beta_2 v^*}\right] = 0 \\ -\frac{1}{r} + \frac{v^*}{r}\beta_1 - \frac{K}{2}\alpha_i^*\beta_1 - \left[\frac{a}{r} - \frac{\theta}{r^2} - \xi_i B e^{\beta_2 v^*}\right]\beta_1 - \xi_i \beta_2 B e^{\beta_2 v^*} = 0, \end{cases} \tag{C.7}$$

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.

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.

Alexander, D. R., Mo, M., and Stent, A. F. (2012). Arithmetic brownian motion and real options. *European Journal of Operational Research*, 219(1):114–122.

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.

Bar-Ilan, A. and Strange, W. C. (1999). The timing and intensity of investment. *Journal of Macroeconomics*, 21(1):57–77.

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.

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.

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.

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.

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.

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.

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.

Dangl, T. (1999). Investment and capacity choice under uncertain demand. *European Journal of Operational Research*, 117(3):415–428.

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.

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

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

ESG, M. P. (2018). Renewable energy report 2018. Technical report, Energy & Strategy Group of Polytechnic University of Milan.

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.

Fanone, E., Gamba, A., and Prokopczuk, M. (2013). The case of negative day-ahead electricity prices. *Energy Economics*, 35:22–34.

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

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

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.

Hagspiel, V., Huisman, K. J., and Kort, P. M. (2016). Volume flexibility and capacity investment under demand uncertainty. *International Journal of Production Economics*, 178:95–108.

IEA (2018). World energy outlook 2018. *International Energy Agency Report*.

Ilic, D., Da Silva, P. G., Karnouskos, S., and Griesemer, M. (2012). An energy market for trading electricity in smart grid neighbourhoods. In *2012 6th IEEE international conference on digital ecosystems and technologies (DEST)*, pages 1–6. IEEE.

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

IPCC (2019). Special report: Global warming of 1.5. Technical report, The Intergovernmental Panel on Climate Change.

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.

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

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

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.

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

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

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.

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.*

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.

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

MIT (2015). The future of solar energy. an interdisciplinary study. *MIT Future of Series*, MIT STUDY ON THE FUTURE OF SOLAR ENERGY:356.

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

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

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

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.

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.

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

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.

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.

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

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.

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.

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.

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.

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.

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.

NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI
Fondazione Eni Enrico Mattei Working Paper Series

Our Working Papers are available on the Internet at the following addresses:
http://www.feem.it/getpage.aspx?id=73&sez=Publications&padre=20&tab=1

NOTE DI LAVORO PUBLISHED IN 2019

1. 2019, FEP Series, Michel Noussan, Effects of the Digital Transition in Passenger Transport - an Analysis of Energy Consumption Scenarios in Europe

2. 2019, FEP Series, Davide Mazzoni, Digitalization for Energy Access in Sub-Saharan Africa : Challenges, Opportunities and Potential Business Models

3. 2019, ET Series, Edilio Valentini, Paolo Vitale, Uncertainty and Risk-aversion in a Dynamic Oligopoly with Sticky Prices

4. 2019, ET Series, Elkhan Richard Sadik-Zada, Andrea Gatto, Determinants of the Public Debt and the Role of the Natural Resources: A Cross-Country Analysis

5. 2019, ET Series, Jian-Xin Wu, Ling-Yun He, ZhongXiang Zhang, Does China Fall into Poverty-Environment Traps? Evidence from Long-term Income Dynamics and Urban Air Pollution

6. 2019, FEP Series, Pier Paolo Raimondi, Central Asia Oil and Gas Industry - The External Powers' Energy Interests in Kazakhstan, Turkmenistan and Uzbekistan

7. 2019, ET Series, Bladimir Carrillo, Present Bias and Underinvestment in Education? Long-run Effects of Childhood Exposure to Booms in Colombia

8. 2019, ES Series, Luca Farnia, On the Use of Spectral Value Decomposition for the Construction of Composite Indices

9. 2019, ET Series, Francesco Menoncin, Sergio Vergalli, Optimal Stopping Time, Consumption, Labour, and Portfolio Decision for a Pension Scheme

10. 2019, FEP Series, Samuel Carrara, Assessing the Techno-economic Effects of the Delayed Deployment of CCS Power Plants

11. 2019, ET Series, Nicola Comincioli, Sergio Vergalli and Paolo M. Panteghini, Business Tax Policy under Default Risk

12. 2019, ET Series, Wolfgang Buchholz, Richard Cornes, Dirk Rübbelke, Matching in the Kolm Triangle: Interiority and Participation Constraints of Matching Equilibria

13. 2019, FEP Series, Achim Voss, The Adverse Effect of Energy-Efficiency Policy

14. 2019, ES Series, Angelo Antoci, Simone Borghesi, Giulio Galdi and Sergio Vergalli, Adoption Gaps of Environmental Adaptation Technologies with Public Effects

15. 2019, ES Series, Ángela García-Alaminos and Santiago J. Rubio, Emission Taxes, Feed-in Subsidies and the Investment in a Clean Technology by a Polluting Monopoly

16. 2019, ES Series, Paolo Casini, Edilio Valentini, Emissions Markets with Price Stabilizing Mechanisms: Possible Unpleasant Outcomes

17. 2019, FEP Series, Kristina Govorukha, Philip Mayer, Dirk Rübbelke, Stefan Vögele, Economic Disruptions in Long-Term Energy Scenarios – Implications for Designing Energy Policy

18. 2019, ES Series, Luca Farnia, Laura Cavalli and Sergio Vergalli, Italian Cities SDGs Composite Index: A Methodological Approach to Measure the Agenda 2030 at Urban Level

19. 2019, FEP Series, Samuel Carrara, Reactor Ageing and Phase-out Policies: Global and European Prospects for Nuclear Power Generation

20. 2019, ET Series, Banchongsan Charoensook, On the Interaction between Small Decay, Agent Heterogeneity and Diameter of Minimal Strict Nash Networks in Two-way Flow Model: A Note

21. 2019, ETA Series, Maria Rosaria Alfano, Claudia Cantabene, Damiano Bruno Silipo, Mafia Firms and Aftermaths

22. 2019, ETA Series, Michele G. Giuranno, Marcella Scrimitore, Giorgos Stamatopoulos, Vertical Integration under an Optimal Tax Policy: a Consumer Surplus Detrimental Result

23. 2019, ETA Series, Alessandro Argentieri, Luciano Canova, Matteo Manera, Coaches on Fire or Firing the Coach? Evidence of the Impact of Coach Changes on Team Performance from Italian Serie A

24. 2019, FEP Series, Kathleen Cohen, Human Behavior and New Mobility Trends in the United States, Europe, and China

25. 2019, FEP Series, Canran Zheng, The Energy Transition in China: Mid-to Long-Term National Strategies and Prospects

26. 2019, FACTS Series, Silvia Beghelli, Gianni Guastella, Stefano Pareglio, Governance Fragmentation and Urban Spatial Expansion: Evidence from Europe and the United States

27. 2019, FEP Series, Liang Nie, ZhongXiang Zhang, “Neighbors as Competitors” or “Neighbors as Partners”: How does Market Segmentation Affect Regional Energy Efficiency in China?

28. 2019, ES Series, Marta Castellini, Francesco Menoncin, Michele Moretto, Sergio Vergalli, Photovoltaic Smart Grids in the Prosumers Investment Decisions: a Real Option Model

Fondazione Eni Enrico Mattei
Corso Magenta 63, Milano – Italia

Tel. +39 02.520.36934
Fax. +39.02.520.36946

E-mail: letter@feem.it
www.feem.it

FEEM
FONDAZIONE ENI
ENRICO MATTEI