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Summary

Due to the deployment of distributed renewable energy sources (e.g., solar), the introduction of communication technologies, and the digitalization of the power system (e.g., smart meters, control devices), energy consumers are switching from passive to active in the management of their energy consumption, production, and storage patterns. In a consumer-centric energy market, Peer-to-Peer (P2P) trading allows consumers and prosumers to directly trade energy without any intermediation by traditional energy suppliers. In this paper, we investigate households' decisions to invest in domestic PV plants coupled with battery storage, namely PV-battery systems (PVBs), and to participate in a local energy community (EC), in which energy quotas can be exchanged among EC members via P2P trading. Thanks to storage and P2P, households can strategically decide their optimal course of action and their optimal energy production/consumption patterns and can actively offer services that other EC participants bid for. In detail, we examine whether P2P trading can increase the value of investments in PVBs and affect the decision on both the optimal investment timing and size. Following the real options approach, we develop a stochastic optimization model. Our results show that ceteris paribus, thanks to P2P trading opportunities, households accelerate investments and invest in larger plants compared to scenarios in which P2P trading in not permitted. According to our findings, at current market prices, it is never optimal to invest immediately and, as P2P traded energy increases, households invest earlier and in smaller plants.

Keywords: PV Plants, Battery Storage, P2P Trading, Real Options, Dynamic Stochastic Optimization

JEL Classification: Q42, C61, D81

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Does P2P trading favor investments in PV-Battery Systems?

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Abstract

Due to the deployment of distributed renewable energy sources (e.g., solar), the introduction of communication technologies, and the digitalization of the power system (e.g., smart meters, control devices), energy consumers are switching from passive to active in the management of their energy consumption, production, and storage patterns. In a consumer-centric energy market, Peer-to-Peer (P2P) trading allows consumers and prosumers to directly trade energy without any intermediation by traditional energy suppliers.

In this paper, we investigate households' decisions to invest in domestic PV plants coupled with battery storage, namely PV-battery systems (PVBs), and to participate in a local energy community (EC), in which energy quotas can be exchanged among EC members via P2P trading.

Thanks to storage and P2P, households can strategically decide their optimal course of action and their optimal energy production/consumption patterns and can actively offer services that other EC participants bid for.

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1 Introduction

The need for deep decarbonization of the energy sector has become a primary objective in the European political and economic debate (European Commission, 2014; European Commission, 2019). The challenge to reach zero-carbon emissions, while enhancing energy system security and energy affordability represents nowadays the fundamental trilemma of power networks (Morstyn et al., 2018).

Among various action plans (e.g., increase in energy efficiency, expansion of renewable energy supply, etc.), the deployment of distributed renewable energy resources (DERs) and the adoption of consumer-level communication and control systems (e.g., smart meters, demand-side management, etc.) are the most important technology trends adopted to address this issue (Morstyn et al., 2018; Dato et al., 2020). DERs, specifically photovoltaic (PV) plants, have been largely adopted worldwide in the last decade thanks to technological innovation, economies of scale effects, and policy incentives.

The global capacity of PV plants reached about 580 GW at the end of 2019, of which about 98 GW were commissioned during 2019 (IRENA, 2019). These new capacity additions demonstrate the major role of PV technologies in the transition to a cleaner electricity sector (Roberts et al., 2019; IRENA, 2021).

Early investments in PV systems used to be driven by government incentives, such as Feed-inTariffs (FiTs). These incentives have now been diminished or eliminated across the world, as PV plants are almost profitable due to sole market remuneration and grid parity has been reached in Europe, the USA, and many other Countries worldwide (Radl et al., 2020; IRENA, 2021). As a result, the focus is no longer on maximizing PV generation, but on maximizing self-consumption to reduce energy costs (Radl et al., 2020).

Due to the increase in DERs market supply, in many EU Countries, self-consumption has been promoted to alleviate the pressure placed by distributed power plants on utility grids (Rodrigues et al., 2020). An increase in self-consumption can be indeed beneficial for (i) energy users to reduce energy costs and (ii) for grid managers to reduce management costs of power networks (Roberts et al., 2019; Koskela et al.,2019; Castellini et al. 2021a; Andreolli et al., 2022).

In this regard, battery energy storage systems represent useful technologies to significantly increase self-consumption and, in turn, reduce supply-demand mismatches. Indeed, surplus energy caused by mismatches between the load demand and the PV generation during peak solar irradiance hours could be curtailed, stored in a battery, or exchanged with other users (Madlener and Specht, 2019; Rodrigues et al., 2020).

It is worth noting that the rapid and continuous deployment of DERs has given rise to the need for the design of a new power system, decentralized and digitalized (Castellini et al., 2021a). In this context, traditional passive consumers become "prosumers" (i.e., agents who produce, consume, and eventually store and share energy locally) and can actively manage their patterns of consumption, generation, storage, and energy sharing (Parag and Sovacool, 2016; Morstyn et al., 2018; Azim et al., 2020; Castellini et al., 2021b).

The new role of prosumers and the paradigm shift in the energy sector have increased the demand for flexibility of energy consumption by end-users (An et al., 2020; Bertolini et al., 2018a; Madlener and Specht, 2019; Dato et al., 2020). To address this issue, Peer-to-Peer (P2P) trading and energy communities (ECs) have emerged as a potential solution to integrate small-scale consumers into energy markets. Directives 2018/2001/EU and 2019/944/EU marked a milestone in the recognition of the centrality of consumers and prosumers in the energy transition and the creation of "integrated competitive, consumer-centered, flexible, fair and transparent electricity markets in the EU" (EC, 2019-Directive 2019/944/EU).

Prosumers and consumers can aggregate in ECs, which can potentially act as nodes in a decentralized, polycentric system of energy production, management, and consumption (Gui et al., 2017; Moroni and Tricarico, 2017), in which they can dynamically trade energy via P2P trading, thus encouraging a sustainable and reliable generation and consumption of energy within the EC (Azim et al., 2020; D'Alpaos and Andreolli, 2021). P2P trading permits not only prosumers to obtain benefits from exchanging surplus energy locally, but also to minimize transmission losses and preserve the stability of the grid and energy supply (Zhang et al., 2018; An et al., 2020; Karami and Madlener, 2022; Wu et al., 2022).

Battery storage and P2P trading provide, therefore, valuable opportunities to improve self-consumption in PV generation, reduce energy costs and decrease peak demand. Furthermore, these technologies give prosumers additional operational flexibility (e.g., active management of self-consumption patterns, energy exchanges with other agents and the grid, etc.) thanks to which they can strategically optimize their production/consumption patterns and increase investment value (Bertolini et al., 2018a; Castellini et al., 2021a; Andreolli et al., 2022) by exercising operating options embedded in the investment and deciding the optimal investment timing and size. This in turn increases investments attractiveness and contributes to the hedging of investment risks. Traditional capital budgeting techniques, which are grounded in the Net Present Value (NPV) rule, such as discounted cash flow analysis, have been largely adopted in the literature to assess the value of investments in DERs, nonetheless, it is widely recognized that they do not model uncertainty properly and fail to capture the value of operating options, i.e. the value of flexibility to adapt and revise later decisions in response to unexpected market events (Dixit and Pindyck, 1994; Trigeorgis, 1996). Indeed, the high uncertainty and irreversibility which characterize investments in DERs make prosumers' strategic decision-making extremely difficult (Martinez Ceseña et al. 2013; Bigerna et al., 2016; Schachter and Mancarella, 2016; Cambini et al., 2016). Although there is flourishing literature on the value of energy storage and the effects of P2P trading on prosumers' behavior and investment decisions, as recently reported by Andreolli et al. (2022) and Castellini et al. (2021a), respectively, there is still some room for unexplored issues related to the combined effects of flexibility generated by energy storage and P2P trading within EC members on the value of investments in PV plants coupled with battery storage, namely PV-battery systems (PVBs).

In this paper, we complement the existing literature and investigate whether P2P trading can add to PVBs value and affect the decision on the optimal investment timing and size. In detail, we provide a theoretical and methodological framework to model the decision of two households to invest in a PVB in a P2P trading scenario. We investigate whether the combined adoption of battery storage systems and the participation in P2P markets can effectively increase the profitability of PVBs and affect the decisions on optimal investment timing and the plant optimal size. To capture the value of managerial and operational flexibilities we develop a real options model to mimic a household investment decision to adopt a PVB plant when P2P trading is admitted. In our setting households are integrated into an EC and can satisfy their energy demand by a) self-consuming PV production, b) storing excess PV production in a battery, and c) exchanging PV production both with the grid and other households who participate in the EC via P2P trading. In a two-agent context, we determine the size of the plant which maximizes the households' net benefit (i.e., minimizes energy costs), and the threshold which triggers the investment. We calibrated and tested our model in the Italian context according to data from the Italian electricity market. We show that P2P trading increases the investment value and encourages households to invest in larger PVBs compared to the size of PVBs that they adopt when P2P trading is not admitted. We prove that the households' flexibility to strategically decide their investment timing and their production/consumption patterns and in addition the possibility they are guaranteed to switch from self-consumption to production permits to increase the PVB investment value. In contrast to standard results in the real options literature, our findings reveal that an increase in the volatility of energy prices accelerates the investment and, in turn, reduces the PVB size. According to our results, it emerges a trade-off between the value of the option to defer the investment and the value of the option to switch which is embedded in the project.

The remainder of the paper is organized as follows. Section 2 briefly presents the relevant related literature; Section 3 discusses the model set-up; Section 4 and 5 present the real options model and investigate the investment value and the optimal investment strategy, respectively; Section 6 provides parameter estimates and illustrates the model calibration; Section 7 describes numerical simulations and discusses main results; Section 8 concludes.

2 Related Literature

We investigate households' decisions to invest in PVBs and exchange energy quotas via P2P trading. By combining investment decisions under uncertainty with optimal investment timing and size we contribute both to the existing literature on the real options approach to investment decisions in the energy sector and the existing literature on investments in PVBs and P2P trading. In detail, we complement the literature that investigates the profitability of investments in PVBs and participation in P2P ECs by residential end-users (Long et al., 2018; Nguyen et al., 2018; Baez-Gonzalez et al., 2019; Zepter et al., 2019). As reported in two recent contributions by Castellini et al. (2021a), D'Alpaos and Andreolli (2020a) and Andreolli et al. (2022), who provide an up-to-date state of the art on this issues, most of the contributions in this research domain combine optimization models with traditional capital budgeting techniques to firstly determine the optimal operation strategy and system size and secondly evaluate the investment's profitability. Nonetheless, the number of contributions in the literature to the optimal investment timing and the value of flexibility of the operating options embedded in investments in PVBs is still limited, specifically for market and regulatory settings where P2P trading is admitted. This paper aims to analyze whether the additional flexibility generated by P2P trading can increase the value of investments in PVBs, thus affecting households' strategic decision-making. Our contribution stems from the seminal piece of work by Bertolini et al. (2018a) and those by Castellini et al. (2021b) and Andreolli et al. (2022) and we complement and extend them, by combining the investigation of the effect on the investment strategy of the managerial flexibility generated by energy storage coupled with PV plants to the investigation on the effect of the managerial flexibility which arises from P2P trading among EC members.

Bertolini et al. (2018a) analyze in a real options framework the decision to invest in a PV plant of households connected to both a smart grid and the national grid. According to their findings, the opportunity of selling energy to the national grid via the smart grid increases the value of investments in domestic PV plants as the households (i.e., prosumers) can optimally exercise the option to decide prosumption quotas and the switching switch from prosumption to pure production according to market conditions. This opportunity, in turn, encourages households to invest in larger PV plants compared with those designed for pure self-consumption when the households are not connected to a smart grid. In line with Bertolini et al. (2018a), Castellini et al. (2021a) develop a real options model to investigate the optimal investment strategy of households that undertake investments in PV plants when P2P trading is admitted. They determine the optimal PV plant size based on the effect of households' self-consumption profiles on P2P trading and show that the shape of households' energy demand and supply curves is crucial to the efficiency of P2P trading.

By contrast, Andreolli et al. (2022) model the decision of households connected exclusively to the national grid to invest in domestic PVBs and capture the value of the embedded managerial flexibility. According to their findings, the opportunity of storing energy via batteries increases the PV investment value and encourages households to invest in larger PV plants compared to those not paired with batteries.

Although it is grounded in traditional capital budgeting techniques and does not capture the value of flexibility, the contribution by Luth et al. (2018) deserves a mention. Luth et al. (2018) investigate the contribution of batteries placed at the end-user level (i.e., individually owned batteries) vs batteries shared among community members (i.e., community-owned batteries) who can benefit from P2P trading. Their results show that batteries and P2P trading contribute to reducing households (i.e., prosumers) energy costs.

The novelty of our contribution resides in the assessment of the value of flexibility induced by energy storage and P2P trading. The value of this flexibility is strongly related to the uncertainty over energy prices. In addition, by developing and implementing a dynamic stochastic optimization model, we determine the PVB optimal investment timing and size. Our objective is twofold: determine whether and to which extent storage and P2P affect the optimal investment strategy and, in turn, to verify whether and to which extent managerial flexibilities that are generated by coupling PV plants and storage in a P2P trading regulatory framework can effectively encourage investments in RES and ECs.

3 Model set up

We investigate the case of household i, currently connected to a national grid under a flat contract, who has to decide whether and when to invest in a PVB to cover part of its energy demand. The adoption of a battery guarantees the storage of surpluses in PV generation and, in turn, the increase in self-consumption quotas. In addition, the household can also decide to create a local EC by connecting its PVB plant to another household j's PVB plant and exchange excess energy production via P2P trading. Consequently, via the increase in self-consumption and energy P2P trading within the local EC, household i can reduce energy quotas purchased from the grid, which are necessary to satisfy its total energy demand. Although households' primary target aims at electricity consumption, P2P trading permits households i and j to interact within the EC and with the grid, thus reducing operational issues related to grid management (e.g., network imbalances, congestions, etc.), and coordinate their actions efficiently.
Our model grounds in the following simplifying assumptions:

Assumption 1

Household i energy demand. Energy demand of household i per unit of time t is normalized to 1 (i.e., 1 Mwh):

$$1Mwh = \xi_i\alpha_i + \rho_i(\alpha_j - \xi_j\alpha_j - s(\alpha_j)) + s(\alpha_i) + \gamma_i, \tag{1}$$

where α_i is the expected PV production per unit of time and represents the control variable of household i, $\xi_i \in [0, 1]$ identifies self-consumed PV production, $s(\alpha_i)$ is PV production stored in the battery, γ_i is grid-purchased energy and, consequently, $\rho_i(\alpha_j - \xi_j\alpha_j - s(\alpha_j))$ is energy purchased from household j to satisfy energy demand. In detail, $\rho_i \in [0, \overline{\rho}_i]$ represents energy quotas supplied by household j, which household i is willing to buy, whereas $\overline{\rho}_i$ represent the maximum of energy quotas, which households can reasonably exchange (Castellini et al., 2021b).

Assumption 2

Energy stored in the battery. Batteries permit to increase self-consumption, by storing excess in PV production during the day-time and discharging it during night-time, when there is no PV generation. Household i's energy quota discharged by the battery is described as follows:

$$s(\alpha_i) = \theta_i\alpha_i \tag{2}$$

where $\theta_i \in (0, 1 - \xi_i)$ is the quota of α_i stored and consumed during night-time to satisfy night demand, and $1 - \xi_i$ is the maximum PV production quota, which can be stored in the battery.

In other words, θ_i represents the increase in self-consumption of household i thanks to the adoption of battery storage[1].

According to literature, battery size in kWh per installed kWp PV power is assumed constant and falls into the range [0.5; 1:5] to guarantee that self-consumption is cost-effective (Luthander et al., 2015; Cucchiella et al., 2016; Quoilin et al., 2016). The adoption of batteries sized larger than 1.5 kWh per installed kWp PV power does not increase significantly self-consumption, as batteries can not discharge completely during night-time, thus limiting storage potential the next day (Weniger et al., 2014a; Weniger et al., 2014b; D'Alpaos and Andreolli, 2020b; Andreolli et al., 2022).

It is worth noting that battery storage is meant to increase solely the self-consumption of household i, regardless of its participation in P2P trading. Indeed, the use of batteries is justified by savings due to its use and not by revenues due to selling to neighbors, as the household having high storage capacity and high excess generation during certain hours can influence the market in other hours, which discourages other households to participate in the P2P market (Paudel et al., 2019).

Assumption 3

Households management of energy exchange. Most of the contributions in literature analyze the profitability of P2P trading by considering an EC constituted by multiple participants, who are connected via bidirectional power and communication flows (Luo et al., 2014; Zhang et al., 2018; Gonzalez-Romera et al., 2019; Paudel et al. 2019). By assuming that P2P markets are active during the daytime when the PV plant is in operation (i.e., between 9.00 a.m. and 6.00 p.m.), they propose a trading scheme, in which a single household at a time has availability of excess energy when the other requires energy. In other words, by acting cooperatively, when households cannot satisfy their demand via their own supply, they can purchase energy from other households that have excess energy to sell (Luo et al., 2014).

For the sake of simplification, we analyze the case of two households i and j which exhibit asymmetric load curves. This assumption is in line with existing literature on local P2P energy markets. As in Castellini et al. (2021a), households i and j behave complementarily in demand and supply of exchanged energy, and, in addition, the quota of energy bought from household i cannot be greater than the excess energy quota of household j. Figure 1 illustrates in its upper side an example of daily load and PV production curves of households i and j, respectively, whereas in its lower side it depicts energy purchased from the grid, energy stored in the battery, energy exchanged, the quota of energy stored and the energy exchanges between households can be satisfied. From this simplification, it is possible to observe that for household i the total energy demand ($1MWh$) is satisfied via energy self-consumption ($\xi_i \alpha_i$), energy stored in the battery ($s(\alpha_i)$), energy purchased from household j ($\rho_i(\alpha_j - \xi_j \alpha_j - s(\alpha_j))$) and energy purchased from the grid (γ_i).

[1] The increase in households' self-consumption due to the use of storage technologies varies depending on their individual load curve, the type, and the size of the technologies applied (Weniger et al., 2014a; Cucchiella et al., 2016; Quoilin et al., 2016; Truong et al., 2016; Kappner et al., 2019).

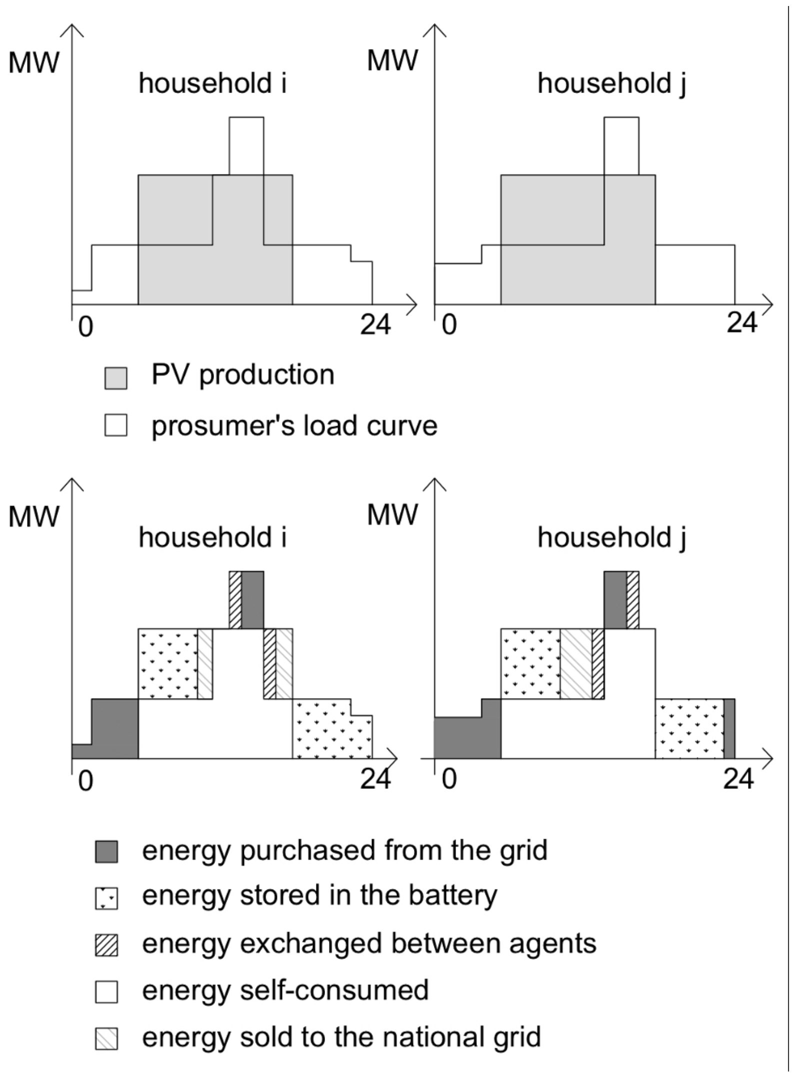

Figure 1: An example of households' daily load demand and PV production curves (Source: our elaboration)

Assumption 4

Energy selling price to the national grid. We assume that the price of grid-purchased energy p is constant over time, whereas the price of energy sold to the national grid v is stochastic and driven by the following Geometric Brownian Motion (GBM):

$$dv(t) = \varphi v(t)dt + \sigma v(t)dz(t) \qquad \text{with } v(t=0) = \nu_0, \tag{3}$$

where $dz(t)$ is the increment of a Wiener process, σ is the instantaneous volatility and φ is the drift term, which is lower than the risk-adjusted discount rate r, i.e. $\varphi \leq r$[2]. According to (3), starting from v_0, the random position of the selling price $v(t)$ for any $t > 0$ has a lognormal distribution, with mean $\ln v_0 + (\varphi - \frac{1}{2}\sigma^2)t$, and variance $\sigma^2 t$ that increases as we look further into the future.

Assumption 5

Price of exchange energy. To participate in a local EC, households i and j agree on the quotas and price w of exchange energy via P2P trading. As in Castellini et al. (2021a; 2021b), we assume that price w is equal to $v(t)$, i.e. the energy selling price to the national grid[3].

As households i and j aim at minimizing energy costs, their investment decisions depend on their energy demand, self-consumption, and the tradeoff between the buying price p and the selling price v (Bertolini et al., 2018a). By considering assumptions 1-5, the net cost of energy paid by household i is:

$$\begin{aligned} C_i(\xi_i, \theta_i, \rho_i, \alpha_i) \;=\;& a\alpha_i + p\gamma_i + w\rho_i(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j) \\ & - w\rho_j(\alpha_i - \xi_i\alpha_i - \theta_i\alpha_i) - v(t)(1-\rho_j)(\alpha_i - \xi_i\alpha_i - \theta_i\alpha_i), \end{aligned} \tag{4}$$

where:

- a_i is the unit maintenance cost of household i's PV plant;
- $a_i\alpha_i$ represents PV plant maintenance costs;
- $p\gamma_i$ is the cost paid for grid-purchased energy;
- $w\rho_i(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j)$ is the cost paid for energy purchased from the household j;
- $w\rho_j(\alpha_i - \xi_i\alpha_i - \theta_i\alpha_i)$ is the revenues on the energy sold to the other household j;
- $v(t)(1-\rho_j)(\alpha_i - \xi_i\alpha_i - \theta_i\alpha_i)$ is the revenues on the energy sold to the national grid.

According to Assumption 5 and by substituting $\gamma_i = 1 - \xi_i\alpha_i - \theta_i\alpha_i - \rho_i(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j)$ from (1) in (4), we can write $C_i(\xi_i, \theta_i, \rho_i, \alpha_i)$ as follows:

$$\begin{aligned} C_i(\xi_i, \theta_i, \rho_i, \alpha_i) \;=\;& a\alpha_i + p\left[1 - \xi_i\alpha_i - \theta_i\alpha_i - \rho_i(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j)\right] \\ & + v(t)\rho_i(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j) - v(t)\rho_j(\alpha_i - \xi_i\alpha_i - \theta_i\alpha_i) \\ & - v(t)(1-\rho_j)(\alpha_i - \xi_i\alpha_i - \theta_i\alpha_i). \end{aligned} \tag{5}$$

[2]This assumption is necessary to guarantee convergence (Dixit and Pindyck, 1994).

[3]Alam et al. (2013) suggest that the price of exchange energy ranges from 0 to grid-purchased energy price. According to Mengelkamp et al. (2017), under perfect information, the price of traded energy converges towards the energy selling price to the national grid.

The net cost of energy $C_i(\xi_i, \theta_i, \rho_i, \alpha_i)$ is decreasing in ξ_i, θ_i and ρ_i iff $v(t) < p$[4]. Therefore, thanks to self-consumption and P2P trading, energy costs can be minimized iff $v(t) < p$. Consequently, optimal (i.e., cost minimizing) self-consumption and trading choices are the following:

$$\begin{cases} p > v(t) \longrightarrow \xi_i \in (0,1]\,,\ \theta_i \in (0, 1-\xi_i]\,, \rho_i \in (0, \overline{\rho_i}] \\ p < v(t) \longrightarrow \xi_i = \theta_i = \rho_i = 0. \end{cases} \tag{6}$$

According to (6), $C_i(\xi_i, \theta_i, \rho_i, \alpha_i)$ becomes:

$$\begin{cases} a\alpha_i + p - v(t)\alpha_i - [\xi_i\alpha_i + \theta_i\alpha_i + \rho_i(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j)]\,(p - v(t)) & \text{if } p > v(t) \\ a\alpha_i + p - v(t)\alpha_i & \text{if } p < v(t). \end{cases} \tag{7}$$

As in Castellini et al. (2021a; 2021b), the following conditions must hold simultaneously to guarantee that the investment minimizes the net cost of energy at the optimal investment timing:

$$\begin{cases} C_i(\xi_i, \theta_i, \rho_i, \alpha_i) > p \\ C_i(\xi_i, \theta_i, \rho_i, \alpha_i) > C_i(\xi_i, \theta_i, 0, \alpha_i), & \text{iff } p > v(t) \\ C_i(\xi_i, \theta_i, \rho_i, \alpha_i) > C_i(0, 0, 0, \alpha_i), & \text{iff } p \leq v(t). \end{cases} \tag{8}$$

The first inequality is always satisfied whenever $v(t) > 0$. The second inequality, which holds when $p > v(t)$, assures that both energy storage and energy P2P trading minimize the net energy costs when self-consumption occurs, that is precisely when $p > v(t)$. Finally, when $p \leq v(t)$, the last inequality assures that the net cost of energy is minimized when there is no self-consumption and produced energy is not P2P traded (i.e., $\xi_i = \theta_i = \rho_i = 0$).

Assumption 6

Total self-consumption quota of household i . In line with Uddin et al. (2017), Bertolini et al. (2018a), D'Alpaos and Andreolli (2020b), it is reasonable to assume that the quota of energy demand that households i can satisfy via a PVB is equal to $\overline{\alpha}_i = \xi_i\alpha_i + \theta_i\alpha_i < 1$. This simplifies the analysis and does not seem excessively restrictive. Since nowadays energy consumption is particularly high in the evening, when PV plants are inactive, battery storage systems are usually adopted to satisfy night-time energy demand and, in turn, reduce energy cost savings (D'Alpaos and Andreolli, 2020b)[5]. As in Bertolini et al. (2018a), by fixing $\overline{\alpha}_i$ the quota of energy demand that household i can satisfy (i.e., total self-consumption quota) via a PVB is endogenously determined once the PV plant and battery size are identified[6].

[4]In fact $\frac{\partial C(\xi_i,\theta_i,\rho_i,\alpha_i)}{\partial \xi_i} = (p-v)\alpha_i$, $\frac{\partial C(\xi_i,\theta_i,\rho_i,\alpha_i)}{\partial \theta_i} = (p-v)\alpha_i$ and $\frac{C(\xi_i,\theta_i,\rho_i,\alpha_i)}{\partial \rho_i} = (p-v_t)(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j)$.

[5]During the day-time, PV production is instantaneously consumed on-site in order to satisfy straightforward energy demand. Consequently, battery storage is adopted to reduce grid-purchased energy. When excess PV production occurs, batteries are charged until the maximum State Of Charge (SOC) is reached. When load increases and cannot be offset by PV production, batteries are discharged until the maximum State Of Discharge (SOD) is reached, afterward and energy quotas are purchased from the grid to satisfy completely energy demand (Colmenar-Santos et al., 2012; Hoppmann et al., 2014; Luthander et al., 2015; Moshovel et al., 2015; Khalilpour and Vassallo, 2016; Hassan et al., 2017; Linssen et al., 2017).

[6]According to many contributions in literature (e.g., Ciabattoni et al., 2014; Kastel and Gilroy-Scott, 2015), PV plants not coupled with storage guarantee a self-consumption quota equal to $30\% - 40\%$ of PV production. Thanks to battery storage, this self-consumption quota can be increased to $60\% - 70\%$ (Weniger et al., 2014b; Luthander et al., 2015; Cucchiella et al., 2017; Andreolli et al., 2022).

Assumption 7

Investment cost. Investment costs paid by household i are described as follows:

$$I_i(\alpha_i) = \frac{k_1}{2}\alpha_i^2 + \frac{k_2}{2}(\theta_i\alpha_i)^2 + P, \tag{9}$$

where $\frac{k_1}{2}\alpha_i^2$ represents PV plant costs, $\frac{k_2}{2}(\theta_i\alpha_i)^2$ represents battery storage costs and P is a fixed cost that represents the sunk cost that households have to pay to exchange energy via P2P trading[7].

Assumption 8

PVB maintenance cost. In line with Bertolini et al. (2018a), Barbose and Darghouth (2019), D'Alpaos and Andreolli (2020b), and Andreolli et al. (2022) PVB maintenance costs are set equal to zero (i.e., $a = 0$).

4 PVB value in a P2P trading scenario

According to the above considerations, when the PVB is operating and connected to the national grid, the PVB allows for flexible choices between two polar cases. Whenever $p < v(t)$, household i minimizes energy costs by selling entirely PV generation to the national grid, i.e. $\xi_i = \theta_i = \rho_i = 0$, and it satisfies entirely energy demand via grid-purchased energy at price p. By contrast, whenever $p > v(t)$, to minimize energy costs household i self-consumes, stores, and exchanges excess PV production quotas (i.e., $\xi_i, \theta_i, \rho_i > 0$).
If we denote by $C_i^0(v(t), \xi_i, \theta_i, \rho_i, \alpha_i)$ the present value of the net cost of energy for any $p > v(t)$, C_i^0 is the sum of the energy costs over the time interval $(t + dt)$ and the continuation value beyond $(t + dt)$. In other words, we define C_i^0 as follows:

$$\begin{aligned} C_i^0(v(t)) \;&=\; [p - v(t)\alpha_i - (\xi_i\alpha_i + \theta_i\alpha_i + \rho_i(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j))(p - v(t))]\,dt \\ &\quad + E\left[e^{-rdt}C_i^0(v(t + dt))\right]. \end{aligned} \tag{10}$$

We can expand the second term on the right side of (10) by using Ito's Lemma, dividing by dt, and finally simplifying the notation to obtain the following second-order differential equation (Dixit and Pindyck, 1994):

$$\frac{1}{2}\sigma^2 v^2 \frac{\partial^2 C_i^0}{\partial v^2} + \varphi v \frac{\partial C_i^0}{\partial v} - rC_i^0 + [p - v(t)\alpha_i - (\xi_i\alpha_i + \theta_i\alpha_i + \rho_i(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j))(p - v(t))] = 0 \quad \text{for } p > v(t). \tag{11}$$

If we denote by $C_i^1(v(t), \xi_i, \theta_i, \rho_i, \alpha_i)$ the present value of the net cost of energy for any $p < v(t)$, we define as C_i^1 as follows:

$$C_i^1(v(t)) = [p - v(t)\alpha_i]\,dt + E\left[e^{-rdt}C_i^1(v(t + dt))\right]. \tag{12}$$

In this latter case, we obtain the following second-order differential equation:

$$\frac{1}{2}\sigma^2 v^2 \frac{\partial^2 C_i^1}{\partial v^2} + \varphi v \frac{\partial C_i^1}{\partial v} - rC_i^1 + [p - v(t)\alpha_i] = 0 \quad \text{for } p < v(t). \tag{13}$$

To solve (11) and (13) we need to introduce the following boundary conditions:

[7] None of the results would change if investment costs were represented by a more general function: $I(\alpha_i) = k\alpha_i^\delta$ where $\delta > 1$.

$$\lim_{v \to 0} \left\{ C_i^0(v(t), \xi_i, \theta_i, \rho_i, \alpha_i) - \frac{(1 - \xi_i\alpha_i - \theta_i\alpha_i - \rho_i(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j))p}{r} + \right. \tag{14}$$
$$\left. + \frac{(\alpha_i - \xi_i\alpha_i - \theta_i\alpha_i - \rho_i(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j))v(t)}{r - \varphi} \right\} = 0,$$

and

$$\lim_{v \to \infty} \left\{ C_i^1(v(t), \xi_i, \theta_i, \rho_i, \alpha_i) - \frac{p}{r} + \frac{\alpha_i v(t)}{r - \varphi} \right\} = 0. \tag{15}$$

According to (14) and (15) and by eliminating the negative and positive roots of the general solution $\Pi = Dv^{\beta_1} + Ev^{\beta_2} + \psi$, respectively (i.e., $E = 0$ for $p > v(t)$ and $D = 0$ for $p < v(t)$), we obtain:

$$C_i(v(t), \xi_i, \theta_i, \rho_i, \alpha_i) = \left\{ \begin{array}{l} C_i^0(v(t), \xi_i, \theta_i, \rho_i, \alpha_i) \\ C_i^1(v(t), \xi_i, \theta_i, \rho_i, \alpha_i) \end{array} \right. = \tag{16}$$
$$= \left\{ \begin{array}{ll} -\frac{(1-\xi_i\alpha_i-\theta_i\alpha_i-\rho_i(\alpha_j-\xi_j\alpha_j-\theta_j\alpha_j))p}{r} + \frac{(\alpha_i-\xi_i\alpha_i-\theta_i\alpha_i-\rho_i(\alpha_j-\xi_j\alpha_j-\theta_j\alpha_j))v(t)}{r-\varphi} + Av(t)^{\beta_1} & \text{if } p > v(t) \\ -\frac{p}{r} + \frac{\alpha_i v(t)}{r-\varphi} + Bv(t)^{\beta_2} & \text{if } p < v(t) \end{array} \right.$$

where $\beta_1 > 1$ and $\beta_2 > 0$ are the positive and negative roots of the characteristic equation $\Phi(\beta) = \frac{1}{2}\sigma^2\beta(\beta - 1) + \varphi\beta - r$, respectively. The terms $Av(t)^{\beta_1}$ and $Bv(t)^{\beta_2}$ in (16) represent, respectively, the value of the option to switch from self-consumption and P2P trading to PV production selling to the national grid if $v(t)$ increases, and vice versa, if $v(t)$ decreases. Constants A and B are obtained by imposing the value-matching and the smooth-pasting conditions at $v(t) = p$:

$$\left\{ \begin{array}{l} A = [\alpha_i\xi_i + \theta_i\alpha_i + \rho_i(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j)] \frac{1}{r-\varphi} \frac{\beta_2\varphi-r}{r(\beta_2-\beta_1)} p^{1-\beta_1} = [\alpha_i\xi_i + \theta_i\alpha_i + \rho_i(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j)] \widehat{A} \\ B = [\alpha_i\xi_i + \theta_i\alpha_i + \rho_i(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j)] \frac{1}{r-\varphi} \frac{\beta_1\varphi-r}{r(\beta_2-\beta_1)} p^{1-\beta_2} = [\alpha_i\xi_i + \theta_i\alpha_i + \rho_i(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j)] \widehat{B} \end{array} \right. \tag{17}$$

which are both linear in $\alpha_i\xi_i + \theta_i\alpha_i + \rho_i(\alpha_j - \xi_j\alpha_j - \theta_j\alpha_j)$.

5 Optimal investment strategy

We can now turn to investigate the optimal investment strategy (i.e., the optimal PV size and the optimal investment timing) and calculate the value of the option to invest.
In line with the above-mentioned assumptions 1-8, we must take into consideration the starting situation, in which household i satisfies its energy demand by purchasing energy from the national grid at a fixed cost p (i.e., idle state), to determine the option value to invest in a PVB. Households will decide to invest in a PVB and P2P trade energy if the PVB adoption assures a positive pay-off (i.e., energy savings) compared to the idle state. Energy savings generated can be described as follows:

$$\pi_i(v(t), \xi_i, \theta_i, \rho_i, \alpha_i) \equiv \frac{p}{r} + C_i(v(t), \xi_i, \theta_i, \rho_i, \alpha_i) = \tag{18}$$
$$= \left\{ \begin{array}{ll} \frac{(\xi_i\alpha_i+\theta_i\alpha_i+\rho_i(\alpha_j-\xi_j\alpha_j-\theta_j\alpha_j))p}{r} + \frac{(\alpha_i-\xi_i\alpha_i-\theta_i\alpha_i-\rho_i(\alpha_j-\xi_j\alpha_j-\theta_j\alpha_j))v(t)}{r-\varphi} + Av(t)^{\beta_1} & \text{if } p > v(t) \\ \frac{\alpha_i v(t)}{r-\varphi} + Bv(t)^{\beta_2} & \text{if } p < v(t). \end{array} \right.$$

Similiarly to Bertolini et al. (2018a), we obtain that, for any $p > v(t)$, $\frac{(\xi_i\alpha_i+\theta_i\alpha_i+\rho_i(\alpha_j-\xi_j\alpha_j-\theta_j\alpha_j))p}{r}$ represents energy savings due to self-consumption, $\frac{(\alpha_i-\xi_i\alpha_i-\theta_i\alpha_i-\rho_i(\alpha_j-\xi_j\alpha_j-\theta_j\alpha_j))v(t)}{r-\varphi}$ the expected revenues from selling the remaining quota of PV generation, whereas $Av(t)^{\beta_1}$ represents

revenues generated by the option to sell entire PV production to the national grid. For any $p < v(t)$, instead, $\frac{\alpha_i v(t)}{r-\varphi}$ represents the expected revenues from selling entire PV production to the national grid and $Bv(t)^{\beta_2}$ the option value to switch back to self-consumption joint to P2P trading.
In order to determine the optimal investment size α_i^* at a given current price $v(t)$, household i maximizes (18) with respect to α_i, net of investment costs $I(\alpha_i)$. In other words, household i has to solve the following maximization problem, in which $NPV(v(t))$ represents the investment Net Present Value, i.e. $NPV = \pi(v(t), \xi_i, \theta_i, \rho_i, \alpha_i) - I(\alpha_i)$:

$$\alpha_i^*(v(t)) = \arg\max \left[NPV(v(t)) \right]. \tag{19}$$

According to Assumption 6, by substituting (18) and (9) in (19) and solving the first-order conditon, the optimal PV size is given by:

$$\alpha_i^*(v(t)) = \max \left[\frac{\frac{v(t)}{r-\varphi}}{k_1 + k_2\theta^2}, \overline{\alpha_i} \right]. \tag{20}$$

In other words, the optimal PV size is represented by the expected discounted flow of revenues generated by an additional unit of capacity $\frac{v(t)}{r-\varphi}$, divided by investment costs incurred to produce this unit (i.e., $k_1 + k_2\theta^2$). It is worth noting that, if price $v(t)$ is very low, household i will decide to invest in a PVB that guarantees exclusively the coverage of the PVB-generated self-consumption quota. Similarly to Bertolini et al. (2018a), in this latter case, the optimal investment strategy is to set $\xi + \theta$ such that $\alpha_i^* = \overline{\alpha_i}$[8].
Let us now turn to the optimal investment timing. We denote by $F(v)$ the value of the option to invest in a PVB connected to a local EC that allows P2P trading. Consequently the maximization problem of household i can be written as follows:

$$F(v) = \sup_t E\left[e^{-rt} NPV(v) \right], \tag{21}$$

where $NPV(v) \equiv NPV(v, \alpha_i^*)$ is given by (18) and (20). By assuming that $F(v)$ is a twice-differentiable function with respect to v, and by implementing Ito's Lemma to expand $dF(v)$, the solution of (21) is given by the following differential equation (Dixit and Pindyck, 1994, p. 179-180):

$$\frac{1}{2}\sigma^2 v^2 \frac{\partial^2 F}{\partial v^2} + \varphi v \frac{\partial F}{\partial v} - rF = 0 \quad for \quad v < v^*. \tag{22}$$

where v^* is the selling price that triggers the investment. The general solution of (22) is $F(v) = Mv^\beta$, where $\beta > 1$ is the positive root of the characteristic equation $\Phi(\beta)$ and M is a constant. When the selling price of energy v is lower than the optimal trigger v^*, it is never optimal to invest. By contrast, as soon as the selling price of energy v hits for the first time v^*, it is optimal to invest and the PV plant's optimal size is $\alpha_i^*(v^*)$. It is worth noting that, whenever $v^* < v_0$, household i will invest immediately and adopt a plant of capacity $\alpha_i^*(v_0)$.
As explained in the previous section, by imposing the value-matching and the smooth-pasting conditions at v^*, we derive that:

[8] In line with Bertolini et al. (2018a), by imposing $\overline{\alpha_i}$, we implicitly assume that the minimum PVB plant size is $\overline{\alpha_i}$. Namely, when $v(t) \to 0$, the Net Present Value of the PVB is given by $NPV(\alpha_i) = \frac{p(\alpha_i(\xi+\theta)+\rho_i(\alpha_j-\xi_j\alpha_j-\theta_j\alpha_j))}{r} - (\frac{k_1+k_2\theta^2}{2})\alpha_i^2$ and $\xi + \theta = \frac{r(k_1+k_2\theta^2)\overline{\alpha_i}}{p} \leq 1$ to ensure investment profitability.

Proposition 1 *(i) If the optimal trigger v^* exists and is lower than p, it is obtained as the numerical solution of the following implicit equation:*

$$\frac{v(t)}{r-\varphi}\left[\frac{1}{k_1+k_2\theta^2}\rho_i\frac{p}{r}(\beta_1-1)-\overline{\alpha_i}(1-\rho_i)(\beta_1-1)-\rho_i\frac{v(t)}{r-\varphi}\frac{1}{k_1+k_2\theta^2}(\beta_1-2)+\right. \tag{23}$$
$$\left.-\widehat{A}v(t)^{\beta_1}\rho_i\frac{1}{k_1+k_2\theta^2}+\frac{v(t)}{r-\varphi}\frac{1}{k_1+k_2\theta^2}\frac{(\beta_1-2)}{2}\right]-P\beta_1+\frac{p}{r}\overline{\alpha_i}(1-\rho_i)\beta_1=0$$

(ii) Whereas, if the optimal trigger v^* exists and is higher than p, it is obtained as the numerical solution of the following implicit equation:

$$\frac{(\beta_1-2)}{2}\left(\frac{v(t)}{r-\varphi}\right)^2\frac{1}{k_1+k_2\theta^2}+\widehat{B}v(t)^{\beta_2}\left[\overline{\alpha_i}(1-\rho_i)(\beta_1-\beta_2)+\right. \tag{24}$$
$$\left.+\rho_i\frac{v(t)}{r-\varphi}\frac{1}{k_1+k_2\theta^2}(\beta_1-\beta_2-1)\right]-P\beta_1=0$$

Proof. *See Appendix A.* ■

It is worth noting that boundary conditions account for both the marginal cost and the marginal revenue to defer the investment decision. The optimal investment strategy is strongly affected by the value of β. The greater the value of β, the larger the option value to postpone the investment.

6 Model calibration

To test the above theoretical results and analyze in detail the decision to invest in a PVB in a P2P trading scenario, as well as to investigate the relationship between the value of being connected to the national grid (which permits households to sell PV production totally or partially) and the optimal investment timing and size, in the following section we provide an empirical application. To calibrate the model we use data from the Italian electricity market over the time interval from 2004 to 2019. According to Assumption 1 households' energy demand is constant over time and normalized to 1 $MWh/year$[9] and, in addition, according to Assumption 3, households are asymmetric in load curves and symmetric in P2P trading, i.e. $\overline{\alpha_i}=\overline{\alpha_j}$ and $\rho_i=\rho_j$.

- $v(t)$ is the price of both energy P2P traded and sold to the national grid. It corresponds to the price paid to households by the Italian Transmission System Operator (TSO) to procure resources needed for the management of the power system (Bertolini et al., 2018a). This selling price is indexed to the Single National Price (PUN), which is established in the Italian Power Exchange (IPEX)[10] and made available on the website of the Italian independent system operator (Gestore dei Mercati Energetici - GME). Based on Biondi and Moretto (2015), Bertolini et al. (2018b), and Andreolli et al. (2022), to estimate the stochastic process underlying energy price evolution over time, we consider PUN hourly prices recorded in the period from April 2004 to December 2019 and in the time interval from 8 a.m. to 7 p.m. We compute average monthly seasonally adjusted prices according to daily averages. Using R software, we tested both the independence assumption (by plotting the autocorrelations of log return $r_t=\frac{\ln p_{t+1}}{\ln p_t}$) and the normality (by plotting

[9]The per-period energy demand is the average of per-period demands registered over a year and accounts for seasonality, atmospheric and climate conditions. In other words $d=\sum_{i=1}^{365}\int_0^{24}l_i(s)ds$, where $l_i(s)$ represents the average hourly load curve.

[10]The Italian Power Exchange (IPEX), managed by GME, is the exchange for electricity (and natural gas) spot trading in Italy. For details, see https://www.mercatoelettrico.org.

the sample data of log returns against the standard normal distribution). Subsequently, the non-stationarity assumption for GBM is verified by implementing the Dickey-Fuller test[11]. Energy price at the beginning of the period, i.e. at time $t = 0$, is $v(t = 0) = 55$ €$/MWh$[12]. The estimated price annual drift and volatility are $\varphi = 0.8\%$ and $\sigma = 42.32\%$, respectively[13].

- p is the grid-purchased energy price. It is set equal to 143€$/MWh$, which corresponds to the maximum electricity price paid by domestic users in the European Market[14].

- PVB investment costs $\frac{k_1}{2}\alpha_i^2 + \frac{k_2}{2}(\theta_i\alpha_i)^2$ take into consideration construction and installation costs (e.g., panel costs, battery costs, inverters, cables), maintenance and operating costs, integration costs, and indirect costs related to efficiency losses in energy production or storage capacity (Bertolini et al., 2018a; D'Alpaos and Andreolli, 2020b; Andreolli et al. 2022). Parameters k_1 and k_2 are estimated according to the approach presented by Bertolini et al. (2018a)[15]. In detail, the average PVB lifetime T is set equal to 25 years (Zucker and Hinchliffe, 2014; Kastel and Gilroy-Scott, 2015; Linssen et al., 2017; Schopfer et al., 2018), whereas $LCOE$ is equal to 90 €$/MWh$ and 110 €$/MWh$, respectively (IEA, 2019; LAZARD, 2019a), and $LCOS$ is equal to 290 €$/MWh$ and 315 €$/MWh$, respectively (Julch, 2016; Schmidt et al., 2017; Few et al., 2018; Schopfer et al., 2018; Comello and Reichelstein, 2019; LAZARD, 2019b). As in Castellini et al. (2021b), the access fee P that households have to pay for participating in the EC amounts to $0.1k_1$.

- r represents the risk-adjusted discount rate that is set equal to 4% and 6%, respectively (Bertolini et al., 2018a; Castellini et al., 2021b; Andreolli et al., 2022).

- As to energy demand quotas, which households can satisfy by PVBs, we assume that $\overline{\alpha_i}$ is equal to $60\% - 70\%$ (Cucchiella et al., 2016; Cucchiella et al., 2017; D'Alpaos and Andreolli, 2020b).

- Finally, the parameter ρ_i, which represents the energy quota that household i wants to exchange with household j via P2P trading, is set equal to 0.10 (Zhang et al., 2018; Sousa et al., 2019; Castellini et al., 2021b).

Table 6.1 summarizes parameter estimates.

[11] Augmented Dickey-Fuller test, in which the alternative hypothesis is stationarity, was performed in R software. The test result is -0,2510 and the $p - value$ is equal to 0.8021. Therefore we failed to reject the null hypothesis.

[12] $v(t = 0)$ is assumed as the average of yearly PUN prices recorded in the time interval from January 2016 to December 2019 by GME.

[13] As in Andreolli et al. (2022), volatility is given by: $\sigma = \sum \frac{(r_i - \hat{m})^2}{n}$, where $\hat{m}$ is the sample mean of r_t, and the drift term is estimated by running the linear regression $r_t = \mu t + \varepsilon_t$, where $\mu = \alpha - \frac{\sigma^2}{2}$ and $\varepsilon_t = \sigma(z_{t+1} - z_t)$. Finally, monthly data are transfomed into annual data as follows: $\sigma_{yearly} = \sqrt{12\sigma^2_{monthly}}$.

[14] The data are in Euro currency and refer to an annual consumption between 2 500 and 5 000 kWh (Band-DC, Medium), excluding taxes and levies.

[15] According to Bertolini et al. (2018a), $k_1 = \frac{2LCOE}{r}(1 - e^{-rT})$ and $k_2 = \frac{2LCOS}{r}(1 - e^{-rT})$, where $LCOE$ is the Levelized Cost Of Energy and $LCOS$ is the Levelized Cost Of Storage.

Parameter	*Description*	*Value*	*Source/Reference*
φ	drift	0.08%	Calibrated on PUN, TSO GME
σ	volatility	42.32%	Calibrated on PUN, TSO GME
v_0	price $v(t)$ at the biginning of time period (€$/MWh$)	54	Calibrated on PUN, TSO GME
p	the fixed buying price of energy	143	Eurostat
T	SHS plant lifetime (years)	25	Kastel and Gilroy-Scott, 2015
r	risk-adjusted discount rate	$4-6\%$	Bertolini et al., 2018; Andreolli et al., 2022; Castellini et al., 2021b
$LCOE$	$LCOE$ for PV plants (€$/MWh$)	$90-110$	Andreolli et al., 2022
k_1	PV plant cost of capital	see Appendix B	Computed, Bertolini et al., 2018
$LCOS$	$LCOS$ for battery (€$/MWh$)	$290-315$	Andreolli et al., 2022
k_2	battery cost of capital	see Appendix B	Computed, Bertolini et al., 2018
P	cost to access to the local energy community	$0.1k_1$	Castellini et al., 2021b
$\overline{\alpha_i}$	household's energy demand satisfied by the SHS	$60\%-70\%$	Ciabattoni et al., 2014; Kastel and Gilroy-Scott, 2015; Cucchiella et al., 2016; Cucchiella et al., 2017; Bertolini et al., 2018
ρ_i	households' exchange energy quota	0.10	Zhang et al., 2018; Sousa et al., 2019; Castellini et al., 2021b

Table 6.1: Parameter estimates

7 Results and comparative statics

In what follows, we present the main results and comparative statics performed with respect to $LCOE$, $LCOS$, φ, σ, $\overline{\alpha_i}$ and ρ_i. Table 7.1 and Table 7.2 shows the optimal selling price v^* that triggers the investment, PVB optimal size α_i^*, P2P traded energy $\rho_i(\alpha_i^*-\overline{\alpha_i})$ and energy sold to the national grid $(1-\rho_i)(\alpha_i^*-\overline{\alpha_i})$, obtained by implementing parameters estimates in Table 6.1 (i.e., benchmark case), different $LCOE-LCOS$ combinations and r equal to 4% and 6%, respectively.
In the benchmark case, for each $LCOE-LCOS$ combination, the optimal trigger v^* is always greater than the current selling price of energy v_0, therefore it is never optimal to invest immediately and the option value to defer investment is positive. Furthermore, thanks to the opportunity of exchanging energy quotas via P2P trading, households will invest in larger plants compared to those adopted in a scenario where P2P trading is not admitted, i.e., $\alpha_i^* > \overline{\alpha_i}$.

It is worth noting that when $r = 6\%$ the optimal trigger v^* is higher than p in all scenarios (Table 7.2) Consequently, households' optimal strategy is to sell entirely PV production to the national grid: the greater the r, the greater the β and, in turn, the greater the option value to postpone the investment. By contrast, when $r = 4\%$, v^* is greater than the buying price of energy p exclusively when $LCOE = 110$ €$/MWh$ and $LCOS = 315$ €$/MWh$. The reason resides in that when investment costs are large, households wait longer for the investment to be profitable. Consequently, the selling price that triggers the investment turns to exceed p.
Compared to previous studies on prosumers' investment decisions in residential PV plants, which do not consider PV plants coupled with storage in a P2P trading scenario (Bertolini et al., 2018a; Andreolli et al., 2020b; Castellini et al., 2021b; Andreolli et al., 2022), our results show that batteries can accelerate investments in PV plants by ensuring higher self-consumption shares and, in turn, larger energy savings. Simultaneously, high investment costs paid for battery adoption are counterbalanced by net benefits deriving from P2P traded energy. By preventing losses in energy quotas not self-consumed, P2P trading permits households to install larger

	LCOS = 290							
$\overline{\alpha}$	LCOE = 90				LCOE = 110			
	v^*	α^*	$\rho\,(\alpha^* - \overline{\alpha})$	$(1-\rho)\,(\alpha^* - \overline{\alpha})$	v^*	α^*	$\rho\,(\alpha^* - \overline{\alpha})$	$(1-\rho)\,(\alpha^* - \overline{\alpha})$
0.60	120.77	1.10	0.05	0.45	125.97	0.98	0.04	0.39
0.70	138.91	1.07	0.04	0.34	143.89	0.97	-	0.97
	LCOS = 315							
$\overline{\alpha_i}$	LCOE = 90				LCOE = 110			
	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$
0.60	121.71	1.08	0.05	0.44	126.78	0.97	0.04	0.33
0.70	140.50	1.05	0.03	0.32	145.32	0.95	-	0.95

Table 7.1: v^* [€$/MWh$], α_i^* $[MWh]$, $\rho_i(\alpha_i^* - \overline{\alpha_i})$ and $(1-\rho_i)(\alpha_i^* - \overline{\alpha_i})$ when $r = 4\%$, $T = 25$ years, $LCOE = 90, 110$ €$/MWh$, $LCOS = 290, 315$ €$/MWh$, $\sigma = 42.32\%$, $\alpha = 0.008$, $\overline{\alpha_i} = 0.6, 0.7$ and $\rho_i = 0.1$.

	LCOS = 290							
$\overline{\alpha}$	LCOE = 90				LCOE = 110			
	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$
0.60	150.73	1.00	-	1.00	154.37	0.87	-	0.87
0.70	171.83	0.97	-	0.97	175.37	0.86	-	0.86
	LCOS = 315							
$\overline{\alpha}$	LCOE = 90				LCOE = 110			
	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$
0.60	151.74	0.99	-	0.99	155.23	0.87	-	0.87
0.70	173.61	0.95	-	0.95	176.92	0.85	-	0.85

Table 7.2: v^* [€$/MWh$], α_i^* $[MWh]$, $\rho_i(\alpha_i^* - \overline{\alpha_i})$ and $(1-\rho_i)(\alpha_i^* - \overline{\alpha_i})$ when $r = 6\%$, $T = 25$ years, $LCOE = 90, 110$ €$/MWh$, $LCOS = 290, 315$ €$/MWh$, $\sigma = 42.32\%$, $\alpha = 0.008$, $\overline{\alpha_i} = 0.6, 0.7$ and $\rho_i = 0.1$.

plants and reduce the optimal investment threshold.

It is noteworthy that investment costs affect α_i^* and v^* differently. An increase in both $LCOE$ and $LCOS$ generates, on the one hand, a delay in investment timing, and, on the other hand, a decrease in investment size. In other words, the lower $LCOE$ and $LCOS$, the shorter the deferral and the larger the PVB size. This result is rather intuitive: whenever investment costs are large, households decide to invest at a later time, which, nonetheless can be shortened by reducing investment size. Self-consumption $\overline{\alpha_i}$ affects results analogously: the higher the $\overline{\alpha_i}$, the longer the deferral, and the smaller the optimal investment size. Nonetheless, α_i^* is always larger than $\overline{\alpha_i}$[16], i.e. the minimum plant size that can only cover self-consumption when $v(t) \to 0$.

Table 7.3 shows some comparative statics performed by varying energy price volatility σ. Two important results emerge: (i) there is a positive relation between α_i^* and v^*; (ii) an increase in uncertainty generates a decrease in both the optimal selling price v^* and investment size α_i^*. The last result is apparently in contrast with findings in the Real Options literature on investment timing flexibility, according to which the higher the uncertainty, the greater the option value of waiting to invest. Nonetheless, when volatility increases, the option to switch, embedded in the investment, makes the investment more beneficial and, consequently, the investment accelerates. In other words, households invest earlier and in smaller plants, thanks to the positive value of the option to switch, which increases the investment value. As in Bertolini et al. (2018a),

[16] We observe the same effect by varying T. Nonetheless, as its effect is negligible, results for different plant lifetimes are not presented.

there is a trade-off between the option value to defer and the option value to switch. There is also a balancing effect of the positive relationship between α_i^* and v^*. Although an increase in uncertainty causes an increase in the option of waiting to invest and, in turn, an increase in investment costs contingent on the plant's size, households may decide to reduce the investment delay by adopting a smaller plant, which entails lower investment costs.
We performed additional comparative statics analyses by varying drift φ (Table 7.4). As φ increases, households accelerate investment (i.e., invest earlier) and install smaller plants. A remarkable exception is when the drift is large enough that the trigger v^* is lower than v_0, and consequently, the investment turns out to be currently profitable. In this scenario, expected energy savings are high enough to induce households to adopt larger plants. When $\varphi = 3\%$ households decide to invest immediately (i.e., $v^* = v_0 = 55$).
Finally, we varied P2P traded energy quotas ρ_i. In detail, whenever ρ_i is low, households invest in a PVB to sell excess energy to the national grid, thus gaining from the mark-up between the buying and the selling price of energy. The effects of changes in ρ_i are clear-cut: by decreasing ρ_i households decide to adopt bigger plants; consequently, there is a delay in the optimal investment timing. This delay is particularly evident for higher $\overline{\alpha_i}$, where the optimal investment scenario is generally $v^* > p = 143$ (Table 7.5), e.g. when $\overline{\alpha_i} = 0.7$, $LCOE = 90/110$ €$/MWh$ and $LCOS = 315$ €$/MWh$, households prefer to sell their entire PV production to the national grid. On the other hand, an high value of ρ_i characterizes those households whose demand curves enable them to trade a greater quota of PV production. As they aim to lower energy costs, by increasing quotas exchange, households decide to accelerate their investment and install lower plants. This finding is consisent with results in Table 7.6, where the optimal investment strategy is always $v^* < p$.
Our results may have interesting policy implications: as investment costs are still relatively high, incentives on investment costs are needed, but they should be combined to policy instruments designed to promote an increase in both self-consumption and P2P traded energy. By looking to the forth (i.e., $\rho_i(\alpha_i^* - \overline{\alpha_i})$) and fifth column (i.e., $(1-\rho_i)(\alpha_i^* - \overline{\alpha_i})$) respectively, it is, in fact, worth noting that quotas of P2P traded energy is very low (between 2% to 9% of households' energy demand), whereas quotas of energy sold to the national grid remains relatively high (between 20% to 50% of PV production).

$\overline{\alpha_i}$	LCOE = 90/ LCOS = 290											
	$\sigma = 25\%$				$\sigma = 35\%$				$\sigma = 45\%$			
	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$
0.60	139.67	1.26	0.07	0.60	126.00	1.14	0.05	0.49	110.10	1.08	0.05	0.43
0.70	155.53	1.20	-	1.15	13.53	1.11	-	1.01	137.40	1.06	0.04	0.32
$\overline{\alpha_i}$	LCOE = 110/ LCOS = 290											
	$\sigma = 25\%$				$\sigma = 35\%$				$\sigma = 45\%$			
	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$
0.60	142.65	1.10	0.05	0.45	130.67	1.01	0.04	0.37	124.45	0.97	0.04	0.33
0.70	158.23	1.07	-	1.07	148.92	0.99	-	0.99	142.58	0.96	0.03	0.23
$\overline{\alpha_i}$	LCOE = 90/ LCOS = 315											
	$\sigma = 25\%$				$\sigma = 35\%$				$\sigma = 45\%$			
	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$
0.60	140.46	1.25	0.06	0.58	126.91	1.13	0.05	0.48	120.05	1.06	0.05	0.42
0.70	156.86	1.17	-	1.17	145.05	1.08	-	1.08	139.03	1.04	0.03	0.31
$\overline{\alpha_i}$	LCOE = 110/ LCOS = 315											
	$\sigma = 25\%$				$\sigma = 35\%$				$\sigma = 45\%$			
	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$
0.60	143.00	1.09	0.05	0.44	131.46	1.00	0.04	0.36	125.29	0.95	0.03	0.32
0.70	159.39	1.05	-	1.05	149.27	0.98	-	0.98	144.03	0.95	-	0.95

Table 7.3: v^* [€$/MWh$], α_i^* [MWh], $\rho_i(\alpha_i^* - \overline{\alpha_i})$ and $(1-\rho_i)(\alpha_i^* - \overline{\alpha_i})$ when $r = 4\%$, $T = 25$ years, $LCOE = 90, 110$ €$/MWh$, $LCOS = 290, 315$ €$/MWh$, $\sigma = 25, 35, 45\%$, $\alpha = 0.008, \overline{\alpha_i} = 0.6, 0.7$ and $\rho_i = 0.1$.

$\overline{\alpha_i}$	LCOE = 90/ LCOS = 290											
	$\varphi = 0\%$				$\varphi = 2\%$				$\varphi = 3\%$			
	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha}_i)$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha}_i)$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$
0.60	16 8.65	1.15	-	1.15	77.07	1.05	0.04	0.40	55.00	1.49	0.09	0.80
0.70	193.67	1.12	-	1.12	89.57	1.04	0.30	0.30	55.00	1.27	0.06	0.51
$\overline{\alpha_i}$	LCOE = 110/ LCOS = 290											
	$\varphi = 0\%$				$\varphi = 2\%$				$\varphi = 3\%$			
	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha}_i)$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha}_i)$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$
0.60	175.17	1.02	-	1.02	80.89	0.94	0.03	0.31	55.00	1.28	0.07	0.61
0.70	200.16	1.01	-	1.01	93.33	0.94	0.02	0.22	55.00	1.11	0.04	0.37
$\overline{\alpha_i}$	LCOE = 90/ LCOS = 315											
	$\varphi = 0\%$				$\varphi = 2\%$				$\varphi = 3\%$			
	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha}_i)$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha}_i)$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$
0.60	169.91	1.13	-	1.13	77.72	1.03	0.04	0.39	55.00	1.47	0.08	0.78
0.70	195.89	1.10	-	1.10	90.69	1.02	0.03	0.29	55.00	1.24	0.05	0.49
$\overline{\alpha_i}$	LCOE = 110/ LCOS = 315											
	$\varphi = 0\%$				$\varphi = 2\%$				$\varphi = 3\%$			
	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$	v^*	α^*	$\rho_i\,(\alpha_i^* - \overline{\alpha}_i)$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha}_i)$	v^*	α_i^*	$\rho_i\,(\alpha_i^* - \overline{\alpha_i})$	$(1-\rho_i)\,(\alpha_i^* - \overline{\alpha_i})$
0.60	176.28	1.00	-	1.00	81.47	0.93	0.03	0.30	55.00	1.26	0.06	0.60
0.70	202.15	0.99	-	0.99	94.34	0.93	0.02	0.20	55.00	1.08	0.04	0.34

Table 7.4: $v^*\,[€/MWh]$, $\alpha_i^*\,[MWh]$, $\rho_i(\alpha_i^* - \overline{\alpha_i})$ and $(1-\rho_i)(\alpha_i^* - \overline{\alpha_i})$ when $r = 4\%$, $T = 25$ years, $LCOE = 90, 110$ $€/MWh$, $LCOS = 290, 315$ $€/MWh$, $\sigma = 42.32\%$, $\alpha = 0, 2, 3\%, \overline{\alpha_i} = 0.6, 0.7$ and $\rho_i = 0.1$.

$\overline{\alpha_i}$	LCOS = 290							
	LCOE = 90				LCOE = 110			
	v^*	α_i^*	$\rho_i\left(\alpha_i^* - \overline{\alpha_i}\right)$	$\left(1-\rho_i\right)\left(\alpha_i^* - \overline{\alpha_i}\right)$	v^*	α_i^*	$\rho_i\left(\alpha_i^* - \overline{\alpha_i}\right)$	$\left(1-\rho_i\right)\left(\alpha_i^* - \overline{\alpha_i}\right)$
0.60	122.76	1.11	0.05	0.46	128.64	0.99	0.03	0.35
0.70	141.84	1.10	0.03	0.36	147.47	0.99	-	0.99
$\overline{\alpha_i}$	LCOS = 315							
	LCOE = 90				LCOE = 110			
	v^*	α_i^*	$\rho_i\left(\alpha_i^* - \overline{\alpha_i}\right)$	$\left(1-\rho_i\right)\left(\alpha_i^* - \overline{\alpha_i}\right)$	v^*	α_i^*	$\rho_i\left(\alpha_i^* - \overline{\alpha_i}\right)$	$\left(1-\rho_i\right)\left(\alpha_i^* - \overline{\alpha_i}\right)$
0.60	123.76	1.10	0.05	0.45	129.52	0.98	0.03	0.35
0.70	143.54	1.07	-	1.07	149.00	0.98	-	0.98

Table 7.5: v^* [€$/MWh$], α_i^* $[MWh]$, $\rho_i(\alpha_i^* - \overline{\alpha_i})$ and $(1-\rho_i)(\alpha_i^* - \overline{\alpha_i})$ when $r = 4\%$, $T = 25$ years, $LCOE = 90, 110$ €$/MWh$, $LCOS = 290, 315$ €$/MWh$, $\sigma = 42.32\%$, $\alpha = 0.008, \overline{\alpha_i} = 0.6, 0.7$ and $\rho_i = 0.0$.

$\overline{\alpha_i}$	LCOS = 290							
	LCOE = 90				LCOE = 110			
	v^*	α_i^*	$\rho_i\left(\alpha_i^* - \overline{\alpha_i}\right)$	$\left(1-\rho_i\right)\left(\alpha_i^* - \overline{\alpha_i}\right)$	v^*	α_i^*	$\rho_i\left(\alpha_i^* - \overline{\alpha_i}\right)$	$\left(1-\rho_i\right)\left(\alpha_i^* - \overline{\alpha_i}\right)$
0.60	118.55	1.07	0.05	0.42	122.99	0.95	0.04	0.31
0.70	135.67	1.05	0.04	0.31	139.95	0.94	0.02	0.22
$\overline{\alpha_i}$	LCOS = 315							
	LCOE = 90				LCOE = 110			
	v^*	α_i^*	$\rho_i\left(\alpha_i^* - \overline{\alpha_i}\right)$	$\left(1-\rho_i\right)\left(\alpha_i^* - \overline{\alpha_i}\right)$	v^*	α_i^*	$\rho_i\left(\alpha_i^* - \overline{\alpha_i}\right)$	$\left(1-\rho_i\right)\left(\alpha_i^* - \overline{\alpha_i}\right)$
0.60	119.43	1.06	0.05	0.41	123.76	0.94	0.03	0.30
0.70	137.15	1.03	0.03	0.29	141.27	0.93	0.02	0.20

Table 7.6: v^* [€$/MWh$], α_i^* $[MWh]$, $\rho_i(\alpha_i^* - \overline{\alpha_i})$ and $(1-\rho_i)(\alpha_i^* - \overline{\alpha_i})$ when $r = 4\%$, $T = 25$ years, $LCOE = 90, 110$ €$/MWh$, $LCOS = 290, 315$ €$/MWh$, $\sigma = 42.32\%$, $\alpha = 0.008, \overline{\alpha_i} = 0.6, 0.7$ and $\rho_i = 0.2$.

8 Conclusions

This paper investigates households' decisions to invest in a domestic PVB and to participate in a local EC. In our setting, households can satisfy their energy demand by a) self-consuming PV production instantly, b) storing excess PV generation in a battery, c) selling energy to the national grid, and/or d) exchanging energy within EC participants via P2P trading. We differentiate between (1) households who are likely to invest in a PVB for selling energy to the national grid and (2) households whose objective is to reduce energy costs by increasing quotas of P2P traded energy.

According to our results, (i) at current market prices, it is never optimal to invest immediately; (ii) the opportunity provided by P2P trading is valuable and thus increases PVB value; (iii) P2P trading encourages investment in larger plants compared to those designed for self-consumption in a scenario which does not admit P2P trading; (iv) as P2P traded energy increases, both the investment timing and size decrease (i.e., households invest earlier and in smaller plants). Whenever self-consumption and P2P traded energy increase, energy sold to the national grid decreases and, consequently, households' self-sufficiency increases. The increase in the self-sufficiency of ECs can positively affect the management of the national grid and future energy systems: if energy fed into the grid from distributed power plants reduces, the system stability increases, and grid management costs decrease.

Our findings show that the greater the volatility of energy prices, the shorter the investment and, in addition, the smaller the PVB size. This result is counterintuitive with respect to standard results in Real Options literature, according to which the greater the volatility, the longer the deferral. The opportunities provided by P2P trading and the related option value to switch from self-consumption to P2P trading and/or sell energy to the national grid, induce households to accelarate investments but reduce the PVB size. Indeed, thanks to the participation in a local EC and P2P trading, househoulds can optimally exercise their option to switch from sole self-consumption to sole production, and thus to increase the PVB investment value.

It is worth noting that batteries permit to increase self-consumption of PV generation and, in turn, guarantee an increase in energy savings. Although currently batteries are still relatively costly, the increase in investment costs due to battery storage adoption offsets the additional managerial flexibility provided by P2P trading. In other words, P2P trading permits households to adopt larger plants and decrease the optimal investment timing. Nevertheless, the PV generation fed into the national grid continues to be very high. This result, in turn, requires the implementation of additional policies to improve system efficiency. Policy supports have to push for technologies that increase both self-consumed and traded energy, and, in turn, improve plant efficiency (e.g., DSM).

Finally, future research will be devoted to including in modeling: (i) different assumptions on households' load demand and (ii) an increase in the number of EC members.

A - Appendix

$\mathcal{A}$) Let us assume that the optimal trigger exists and is lower than p. From (9), (17) and (18) and by substituting $\alpha_i^* = \alpha_j^* > \overline{\alpha_i} = \overline{\alpha_j}$ in (17) and (18), the project NPV is given by:

$$\begin{aligned} NPV(v(t)) &= \frac{(\overline{\alpha_i} + \rho_i(\alpha_j^* - \overline{\alpha_j}))p}{r} + \frac{(\alpha_i^* - \overline{\alpha_i} - \rho_i(\alpha_j^* - \overline{\alpha_j}))v(t)}{r-\varphi} + \\ & +(\overline{\alpha_i} + \rho_i(\alpha_j^* - \overline{\alpha_j}))\widehat{A}v(t)^{\beta_1} - (\frac{k_1+k_2\theta^2}{2})\alpha_i^{*2} - P = \\ & \overline{\alpha_i}(1-\rho_i)\frac{p}{r} + \rho_i\frac{\frac{v(t)}{r-\varphi}}{k_1+k_2\theta^2}\frac{p}{r} - \rho_i\frac{\left(\frac{v(t)}{r-\varphi}\right)^2}{k_1+k_2\theta^2} - \overline{\alpha_i}(1-\rho_i)\frac{v(t)}{r-\varphi} + \\ & + \left(\overline{\alpha_i}(1-\rho_i) + \rho_i\frac{\frac{v(t)}{r-\varphi}}{k_1+k_2\theta^2}\right)\widehat{A}v(t)^{\beta_1} + \frac{1}{2}\frac{\left(\frac{v(t)}{r-\varphi}\right)^2}{k_1+k_2\theta^2} - P, \end{aligned} \tag{A.1}$$

with $NPV(0) = \overline{\alpha_i}(1-\rho_i)\frac{p}{r} - P > 0$ and $NPV'(0) = -\overline{\alpha_i}(1-\rho_i)\frac{1}{r-\varphi} + \frac{1}{r-\varphi}\rho_i\frac{1}{k_1+k_2\theta^2}\frac{p}{r} < 0$.
In order to determine the optimal trigger v^*, we impose the following matching-value and smooth-pasting conditions:

$$\begin{aligned} Mv(t)^{\beta_1} &= \overline{\alpha_i}(1-\rho_i)\frac{p}{r} + \rho_i\frac{\frac{v(t)}{r-\varphi}}{k_1+k_2\theta^2}\frac{p}{r} - \rho_i\frac{\left(\frac{v(t)}{r-\varphi}\right)^2}{k_1+k_2\theta^2} - \overline{\alpha_i}(1-\rho_i)\frac{v(t)}{r-\varphi} + \\ & + \left(\overline{\alpha_i}(1-\rho_i) + \rho_i\frac{\frac{v(t)}{r-\varphi}}{k_1+k_2\theta^2}\right)\widehat{A}v(t)^{\beta_1} + \frac{1}{2}\frac{\left(\frac{v(t)}{r-\varphi}\right)^2}{k_1+k_2\theta^2} - P, \end{aligned} \tag{A.2}$$

$$\begin{aligned} \beta_1 Mv(t)^{\beta_1-1} &= \frac{1}{r-\varphi}\rho_i\frac{1}{k_1+k_2\theta^2}\frac{p}{r} - 2\rho_i\frac{v(t)}{(r-\varphi)^2}\frac{1}{k_1+k_2\theta^2} - \overline{\alpha_i}(1-\rho_i)\frac{1}{r-\varphi} + \\ & + \overline{\alpha_i}(1-\rho_i)\beta_1\widehat{A}v(t)^{\beta_1-1} + (\beta_1+1)\frac{1}{r-\varphi}\rho_i\frac{1}{k_1+k_2\theta^2}\widehat{A}v(t)^{\beta_1} + \frac{v(t)}{(r-\varphi)^2}\frac{1}{k_1+k_2\theta^2}. \end{aligned} \tag{A.3}$$

(A.3) can be rearranged and substituted into (A.2) as follows:

$$\begin{aligned} Mv(t)^{\beta_1} = & \frac{1}{\beta_1}\frac{v(t)}{r-\varphi}\rho_i\frac{1}{k_1+k_2\theta^2}\frac{p}{r} - \frac{2}{\beta_1}\left(\frac{v(t)}{r-\varphi}\right)^2\rho_i\frac{1}{k_1+k_2\theta^2} - \frac{1}{\beta_1}\overline{\alpha_i}(1-\rho_i)\frac{v(t)}{r-\varphi} + \\ & + \overline{\alpha_i}(1-\rho_i)\widehat{A}v(t)^{\beta_1} + \frac{\beta_1+1}{\beta_1}\frac{v(t)}{r-\varphi}\rho_i\frac{1}{k_1+k_2\theta^2}\widehat{A}v(t)^{\beta_1} + \frac{1}{\beta_1}\left(\frac{v(t)}{r-\varphi}\right)^2\frac{1}{k_1+k_2\theta^2}, \end{aligned}$$

$$\begin{aligned} & (\beta_1-1)\rho_i\frac{\frac{v(t)}{r-\varphi}}{k_1+k_2\theta^2}\frac{p}{r} - (\beta_1-2)\rho_i\frac{\left(\frac{v(t)}{r-\varphi}\right)^2}{k_1+k_2\theta^2} - (\beta_1-1)\overline{\alpha_i}(1-\rho_i)\frac{v(t)}{r-\varphi} + \\ & -\rho_i\frac{\frac{v(t)}{r-\varphi}}{k_1+k_2\theta^2}\widehat{A}v(t)^{\beta_1} + \frac{\beta_1-2}{2}\frac{\left(\frac{v(t)}{r-\varphi}\right)^2}{k_1+k_2\theta^2} = P\beta_1 - \beta_1\overline{\alpha_i}(1-\rho_i)\frac{p}{r}. \end{aligned} \tag{A.4}$$

By rearranging (A.4), we obtain the following equation to be solved numerically in order to determine the optimal trigger v^*:

$$\frac{v(t)}{r-\varphi}\left[(\beta_1-1)\rho_i\frac{1}{k_1+k_2\theta^2}\frac{p}{r}-(\beta_1-2)\rho_i\frac{\frac{v(t)}{r-\varphi}}{k_1+k_2\theta^2}-(\beta_1-1)\overline{\alpha_i}(1-\rho_i)+\right. \tag{A.5}$$

$$\left.-\rho_i\frac{1}{k_1+k_2\theta^2}\widehat{A}v(t)^{\beta_1}+\frac{\beta_1-2}{2}\frac{\frac{v(t)}{r-\varphi}}{k_1+k_2\theta^2}\right]=P\beta_1-\beta_1\overline{\alpha_i}(1-\rho_i)\frac{p}{r}.$$

$\mathcal{B}$) Let us now assume that the optimal trigger v^* exists and is higher than p. As previously, from (9), (17) and (18) and by substituting $\alpha_i^*=\alpha_j^*>\overline{\alpha_i}=\overline{\alpha_j}$ in (17) and (18), the project NPV can be described as follows:

$$\begin{aligned} NPV(v(t)) &= \frac{\alpha_i^* v(t)}{r-\varphi}+(\overline{\alpha_i}+\rho_i(\alpha_j^*-\overline{\alpha_j}))\widehat{B}v(t)^{\beta_2}-(\frac{k_1+k_2\theta^2}{2})\alpha_i^{*2}-P \\ &= \frac{1}{2}\frac{\left(\frac{v(t)}{r-\varphi}\right)^2}{k_1+k_2\theta^2}+\left[\overline{\alpha_i}(1-\rho_i)+\rho_i\frac{\frac{v(t)}{r-\varphi}}{k_1+k_2\theta^2}\right]\widehat{B}v(t)^{\beta_2}-P, \end{aligned} \tag{A.6}$$

where the first term $\frac{1}{2}\frac{\left(\frac{v(t)}{r-\varphi}\right)^2}{k_1+k_2\theta^2}$ dominates as $v(t)\to\infty$. Then, we impose the matching-value and the smooth-pasting conditions as follows:

$$Mv(t)^{\beta_1}=\frac{1}{2}\frac{\left(\frac{v(t)}{r-\varphi}\right)^2}{k_1+k_2\theta^2}+\left[\overline{\alpha_i}(1-\rho_i)+\rho_i\frac{\frac{v(t)}{r-\varphi}}{k_1+k_2\theta^2}\right]\widehat{B}v(t)^{\beta_2}-P \tag{A.7}$$

$$\beta_1 Mv(t)^{\beta_1-1}=\frac{v(t)}{(r-\varphi)^2}\frac{1}{k_1+k_2\theta^2}+\overline{\alpha_i}(1-\rho_i)\beta_2\widehat{B}v(t)^{\beta_2-1}+(\beta_2+1)\rho_i\frac{1}{r-\varphi}\frac{1}{k_1+k_2\theta^2}\widehat{B}v(t)^{\beta_2} \tag{A.8}$$

By rearranging (A.8) and substituting it into (A.7), we obtain the following eqaution:

$$\frac{\beta_2-1}{2}\frac{\left(\frac{v(t)}{r-\varphi}\right)^2}{k_1+k_2\theta^2}+\left[\overline{\alpha_i}(1-\rho_i)\left(\beta_1-\beta_2\right)+(\beta_1-\beta_2-1)\rho_i\frac{\frac{v(t)}{r-\varphi}}{k_1+k_2\theta^2}\right]\widehat{B}v(t)^{\beta_2}=P\beta_1. \tag{A.9}$$

B - Appendix

Table B.1 shows investment costs k_1 and k_2 for different $LCOE - LCOS$ combinations and $r = 4\%.6\%$.

	$T(year)$	k_1	
		$r = 4\%$	$r = 6\%$
LCOE $= 90$ €$//MWh$	25	2844	2330
LCOE $= 110$€$/MWh$	25	3476	2848
	$T(year)$	k_2	
		$r = 4\%$	$r = 6\%$
LCOS $= 290$ €$/MWh$	25	9165	7509
LCOS $= 315$ €$/MWh$	25	9955	8157

Table B.1: Investment costs k_1 and k_2 for $r = 4, 6\%$, $T = 25$ years, $LCOE = 90, 110$ €$/MWh$ and $LCOS = 290, 315$ €$/MWh$.

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