Households' investments in renewable energy and peer-to-peer trading
Preliminary draft

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Abstract

Peer-to-peer (P2P) trading allows prosumers and consumers of electricity to exchange energy with each other outside the traditional centralised system. In this paper, we consider an eco-neighborhood in which individuals can invest in a renewable energy source (RES) and sell their excess power to the energy system at a given price, the feed-in-tariff (FiT) or to their neighbours on a P2P platform. We show that, in the absence of investment externalities, an appropriate FiT is sufficient to induce the first best investment and trade level and P2P has no value added. On the contrary, when negative externalities exist, P2P trading is necessary to restore efficiency.

Keywords: *Renewable energy sources, peer-to-peer, decentralized energy systems*

JEL Codes: *L14, L81, L94, Q4*

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1 Introduction and litterature review

The deployment of renewable energy sources by households have grown in size in the past decades, and the topic has gained the interest of both practioners and academicians. At the european level, the adoption of the Clean Energy Package (CEP) and the Renewable Energy Directive (RED)[1] will allow the development of new models for energy generation and trading.

As the energy market is getting more decentralized, consumers are getting more control over their production and their consumption behavior. The RED recognizes active consumers as part of the energy market, where they have the right to sell the self-generated electricity. Because different business models have emerged following the decentralization of the energy market, and the need to have a clear regulation for each of them, the RED clearly distinguishes between Energy Communities (EC), and Peer-to-Peer trading (P2P). EC are created when the Distributed Energy Resources (DER) are collectively owned to generate the electricity for the members of the community. When the DER are individually owned and managed, prosumers can exchange the energy surplus with their neighbours through a Peer-to-Peer (P2P) exchange contract. Typically, a consumer that engages in a local trade will have two contracts, one with a traditional electricity supplier and one with the other members of the P2P exchange. The terms and conditions of the trading agreement are decided between the peers, with no supervision from the centralized system. However, when the partners of the exchange use the public distribution grid infrastructure to share the energy produced by their installions, they are subject to the charges borne by final consumers that do not take part in the exchange. These charges should be cost-reflective and proportionate to the electricity fed into the grid.

In most countries, the regulators do not allow P2P local energy markets, the CEP urges national regulators to provide a framework for the development of these markets. Though P2P trading is still at an early stage, it would be an essential constituent of the energy system to solve some of the problems

[1] Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources.

that emerge with the growth of prosumers and investments in renewable energy sources. When households sell their excess self-produced energy, they decrease peak loads and reduce the central grid distribution costs.

In particular, this paper proposes two main insights. First, the optimal level of a household's investment in photovoltaic (PV) installations depends on the cost of investment compared to the cost of importing energy from the centralized system. A household will invest in a PV if the net benefit from the investment is positive. Second, a generous FiT can lead to over-investment in PV capacities that will generate negative externalities. This is comes because the surplus of energy will not be consumed within the local grid and has to be injected to the central distribution network with a higher cost for the system. On the other side, with a low FiT, households will invest in PV capacities that satisfy their own auto-consumption. This level of investment is sub-optimal, the reason is that other households part of the same microgrid will have to import their energy from the central system with a higher network distribution cost. In this respect, there is no linear FiT that can lead to the efficient level of investment. P2P trading presents a solution to correct for the inefficiency of this market mechanism and to foster local energy production and consumption[2].

This paper is related to (at least) two strands of the literature. First, it pertains to the literature on decentralised energy systems. There exists a rich litterature on the development of energy communities (EC) and microgrigds. Abaday et al.(2017) study the viability of the community by using a cooperative game theory approach, they find that inadequate gain sharing may jeopardize the stability of a community but if aggregation benefits can compensate coordination costs then the community may be stable. In another paper, the same authors (2018) find that the development of a community depends on grid tariffs, and that the structure of the latter may lead to potential PV over-investment.

[2]The main objective of the European Commission is to promote local energy communities and local energy consumption

Lately, the litterature on P2P trading has grown in importance with a special focus on digital platforms and blockchains. Sousa et al.(2019) provide an overview of P2P markets. Mengelkamp et al.(2018) deals with the fact that consumers and prosumers can trade by using a P2P operating condition in microgrid energy markets without central intermediaries like an aggregator. More precisely, the authors investigate the incentives, both for consumers and prosumers, to participate and to invest in the P2P platform, and the incentives to balance locally supply and demand. On the pricing mechanism, they suggest a price above the taxes and fees of the traditional energy price. Without formal proof, they conclude that local energy trading is beneficial to both parties if the average energy price is lower than the external grid price. Cortade and Poudou (2019), analyze new models of exchange of electricity and their impact on household's investments in RES. They also investigate the design of exchange platforms that give prosumers incentives to engage in local trading.
Second, it is contributes to the existing litterature on feed-in-tariffs. Couture et al.(2009) provide a review of the different feed-in-tariff renumeration models. Lesser and Su (2008) propose a two-part feed-in-tariff that has a capacity component and a market-based component.

To the best of our knowledge, the present paper is the first attempt to study the pricing mechanism of local trading from an economic perspective and formally models the effect of the feed-in-tariff on the level of investment in RES. In this paper we derive a theoritical model to show how P2P trading can restore efficiency when individuals' investments are not welfare maximising. We also derive the equilibrium price at which both the prosumers and the consumers are willing to exchange energy outside the centralised system. We use a cost-benefit analysis to show that independent investments in PV installations depends on the level of feed-in-tariffs and that the efficient level of investment is achieved when households sign a P2P exchange contract.

2 Model

We model an electric system where residential consumers (households) interact with a centralized production/distribution system and between each other. Households are located in different neighborhoods and local exchanges of energy within a neighborhood is supposed to be cheaper than exchanges with more distant neighborhoods.

2.1 Households

There are n agents (households) denoted by A_i, $i = 1, 2, ..., n$, who live in adjacent houses (same block) and are connected to the same energy feeder. Each day, there are two consumption periods that we index by t. We distinguish day (peak) and night consumption: $t \in \{d, n\}$. Agent i has a given energy consumption (q_i^d, q_i^n), the consumption is expressed in kilowatt-hour (kWh).

There are n_1 agents, $n_1 \subsetneq n$, denoted by A_j, $j = 1, ..., n_1$, who can invest in a PV, while the other agents $n_2 = n - n_1$ cannot either due to limited space or inadequate rooftop. The agents can install a PV with a production capacity of k_j during daytime (and zero at nighttime), with a unit cost equal to c. For the A_j agents, the PV production capacity is a fraction $\alpha_j = \frac{k_j}{q_j^d}$ of their daytime consumption, and $\alpha_j \in [0, \bar{\alpha}_j]$ where $\bar{\alpha}_j$ is the maximum installation capacity given the living area. We assume that $\bar{\alpha}_j > 1$, i.e., the agents can invest in an installation that has a production capacity greater than their daytime consumption.

When $\alpha_j = \bar{\alpha}_j$, the excess power is injected to the grid and the agent receives a remuneration for the energy exported given by a linear feed-in-tariff p^{FiT} in € per kWh. The agent does not have to pay an injection fee for exporting power.

We assume that first the agents decide simultanously on the capacity of the PV installations. The optimal level of investment is achieved when the cost-benefit for both, the agent and the system, are aligned.

In this setting, we do not consider socio-economic reasons (supporting local energy production) or environmental objectives.

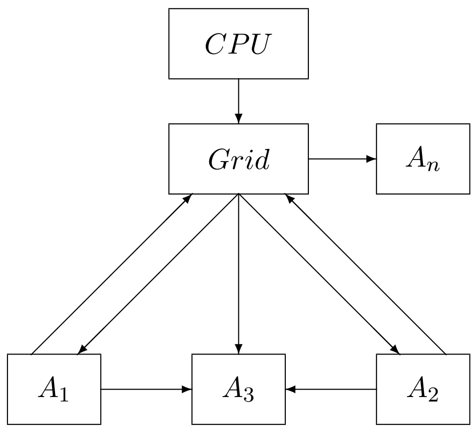

Figure 1: A representation of the energy flow between three agents, A_1 and A_2 are prosumers and form a P2P exchange with A_3.

2.2 Energy system

There are two main actors in the energy system: centralized energy retailers/producers and the grid. All agents are connected to the grid and they have a contract with an energy supplier.

The energy can be produced by centralized production units (CPU) at period t at cost r^t per kWh, we suppose that $r^d > r^n$, i.e., energy production is cheaper during the night than during the day. Energy retailers sell electricity from CPU to the agents. We suppose that the retail sector is competitive and that the energy price is equal to the production cost $g^t = r^t$.

The grid is managed by a grid operator who charges a grid fee per distributed kWh. The grid is used for two types of exchanges: centralized and local exchanges. There are two types of centralized exchanges: power exchanges between the CPU and an agent and power exchanges between two agents in different neighborhoods. Local exchanges are power exchanges between two agents in the same neighborhood. We suppose that, for the grid, centralized exchanges have a cost θ^c and local exchanges a cost θ^l per kWh and that centralized exchanges are more costly than local ones: $\theta^c \geq \theta^l$.

In addition, the grid is in charge of paying the FiT to the prosumers.

When the grid buys energy, it resells it to the retailers at the competitive price. This means that the net cost of the FiT for the grid is equal to $p^{FiT} - g^d$. The FiT and the network fee must be such that the grid breaks even.[3]

In our model, the electricity must be produced to match households' consumption. The electricity system is efficient if it minimizes the total cost of production and transport given consumption. Given that consumption is fixed, cost minimization is equivalent to welfare maximisation.

2.3 First-best level of investment

In this section, we determine the first-best level of investment. As a benchmark, we determine the total cost for the energy system when all the households consume electricity from the CPU, i.e., when there are no decentralized investments by the households.

$$\bar{C} = \sum_{t=d,n} \sum_{i=1}^{n} q_i^t (g_i^t + \theta^c)$$

An investment by the agent is profitable if it decreases the cost below $\bar{C}$. We distinguish three cases depending on the value of c.

First, it is optimal for an agent to invest to cover his daytime consumption if the investment cost is smaller than the total cost of buying electricity from CPU, that is if:

$$c \leq g^d + \theta^c \tag{1}$$

Second, it is optimal to make an investment that exceeds auto-consumption and consume the power surplus locally if:

$$c \leq g^d + \theta^c - \theta^l \tag{2}$$

Finally, it is optimal to make an investment that exceeds auto-consumption

[3] We suppose that the grid's fixed costs are covered by a fixed fee.

and consume the power surplus either locally or in another neighborhood if:

$$c < g^d \tag{3}$$

Equations (1), (2), and (3) define the first-best level of investment. Given that three conditions are not mutually exclusive, we can say that:

- If condition (3) is satisfied, the optimal investment is: $k_j = \bar{k}_j$, $\forall j \in n_j$. Equivalently, we can say that the optimal investment is such that $\alpha_j \geq 1 \, \forall j \in n_j$.

- If condition (2) is satisfied but condition (3) is not, the optimal investment depends on the following condition:

  $$\sum_{j \in n_j} \bar{k}_j \leq \sum_{i \in n_i} q_i^d \tag{4}$$

  If Equation (4) is satisfied, the total production within the neighborhood is insufficient to cover the total consumption within daytime. In this case, the optimal investment is: $k_j = \bar{k}_j$, $\forall j \in n_j$ and the neighborhood still imports energy from the CPU.

  If Equation (4) does not hold, if all the households invest at their maximum capacity then the local production exceeds the local consumption and the electricity must be sold to another neighborhood. However, under condition (2) such an exchange is inefficient. Hence, the optimal investment must be such that auto-consumption is maximized and the total production does not exceed the local consumption. That is: (i) for the agents $j \in n_j$ such that $\bar{k}_j \leq q_j^d$, $k_j = \bar{k}_j$, (ii) for the agents $j \in n_j$ such that $\bar{k}_j > q_j^d$, $q_i^d \leq k_j \leq \bar{k}_j$ and $\sum_{j \in n_j} \bar{k}_j = \sum_{i \in n_i} q_i^d$.

- If condition (1) is satisfied but condition (2) is not, the optimal level of investment is: $k_j = \min[\bar{k}_j, q_j^d] \, \forall j \in n_j$.

Definition 1 **Investment externality** The investment of an agent (or a group of agents) A_j exerts an externality on agent A_k when the investment by A_j changes the system's value of the investment by agent A_k. The externality could be positive or negative.

In the above cases, there are investment externalities in the case when $g^d < c < g^d + \theta^c - \theta^l$ and equation (4) does not hold. In this case, the value of the investment by agent A_k depends on whether the total consumption is already covered by the investment of the other agents or not. When the consumption of the neighborhood is not covered by the installed PV capacity, an investment of size $k = 1$ by A_k has a net benefit of $g^d - \theta^l - c$ while if the consumption is fully covered, the benefit falls to $g^d - \theta^c - c$. In this case, the externality is positive.

3 Decentralized investment decisions

We now consider the situations in which individuals decide on their investment level. We consider the following game. The DSO (or the system's regulator) has the objective of promoting efficiency and to that end, it fixes the network fee θ^c that consumers pay when they withdraw electricity from the grid and the p^{FiT} that the prosumers receive when they inject electricity to the grid. Given θ^c and p^{FiT}, consumers in n_1 decide on their investment level k_j. For the moment, we do not consider the possibility to make bilateral trade in the neighborhood.

3.1 Investment by the agents

For an agent, the marginal return of its investment in a DPU is given by:

$$MR_j = \{ \begin{array}{ll} g^d + \theta^c & \text{for } k_j \leq q_j^d \\ p^{FiT} & \text{for } k_j > q_j^d \end{array}$$

To determine the investment level, one should compare the marginal return with the marginal cost c. We can then establish the following:

Lemma 1 *For $p^{FiT} \leq c \leq g^d + \theta^c$, the investment of agent A_j is given by* $\max[q_j^d, \bar{k}_j]$. *For $c \leq g^d + \theta^c, p^{FiT}$, the investment of agent A_j is given by* $\bar{k}_j$.

3.2 Pricing by the DSO

The DSO sets both θ^c and p^{FiT}. The problem is to minimize the system's cost while guaranteeing a non-negative profit to the DSO. We will consider the case in which the DSO sets a tariff equal to the distribution cost θ^c and we will show that this tariff is indeed optimal.

3.3 Scenario 1: Investments without externalities

We consider that the n_1 agents A_j, $j = 1, 2, ...n_1$, install a PV with capacities that cover their respective energy consumption at daytime: $\sum k_j^* = \sum q_j^d$ and $\alpha_j = \alpha^* = 1$.

The optimality condition for A_j:

$$C_j(k) = ck_j^* \tag{5}$$

$$ck_j^* \leq (g^d + \theta^c)q_j^d \tag{6}$$

given that $k_j^* = q_j^d$,

$$c^* \leq g^d + \theta^c \tag{7}$$

Proposition 1 The agents will invest in a PV capacity that covers their own daytime consumption if the unit cost of the installation is lower than the opportunity cost.

3.4 Scenario 2: Investments with positive externalities

3.4.1 Case 1 $c < g^d + \theta^c - \theta^l$

We consider that the n_1 agents A_j, $j = 1, 2, ..., n_1$, install a PV. The installations of A_l, $l = 1, 2, ..., L$, have a production capacity that exceeds their daytime consumption, $k_l^* > q_l^d$ and $\alpha_l^* = \bar{\alpha}_l$. The installations of A_m, $m = L + 1, ..., n_1$, cover their own daytime consumption, $k_m^* = q_m^d$ and $\alpha_m^* = 1$. We assume that $\sum_j k_j^* \leq \sum_i q_i^d$, $i = 1, ..., n$. A_l will inject the excess energy to the local distribution network to be consumed by A_i, $i \in n_2$, with a cost of θ^l per unit, and for which he receives p^{FiT} per unit.

The optimality constraint for A_m is similar to that of scenario 1.

The optimality constraint for A_l:

$$c\alpha_l^* q_l^d - (\alpha_l^* - 1)q_l^d(p^{FiT} - \theta^l) \leq cq_l^d \tag{8}$$
$$p^{FiT} \geq c + \theta^l \tag{9}$$

The optimality constraint for the system:

$$c\alpha_l^* q_l^d + (\alpha_l^* - 1)q_l^d\theta^l \leq cq_l^d + (\alpha_l^* - 1)q_l^d(g^d + \theta^c) \tag{10}$$
$$c \leq (g^d + \theta^c) - \theta^l \tag{11}$$

All constraints are satisfied if:

$$p^{FiT} \geq (g^d + \theta^c) - \theta^l + \theta^l \tag{12}$$
$$p^{FiT^*} = g^d + \theta^c \tag{13}$$

Proposition 2 When $c < g^d + \theta^c - \theta^l$ and p^{FiT} is equal to the opportunity cost, the *first-best* is achieved when $\sum_j k_j \leq \sum_i q_i$, $j \subset i$. In such case, the investments of the agents generate positive externalities.

3.4.2 Case 2 $c < g^d$

We consider that the n_1 agents A_j, $j = 1, 2, ..., n_1$, install a PV with a production capacity that exceeds their daytime consumption: $k_j > q_j^d$ and $\alpha_j^* = \bar{\alpha}_j$. We assume that: (i) $\sum_{j=1}^{n_1} k_j > \sum_{i=1}^{n} q_i^d$; (ii) $\sum_{j=1}^{n_1}(\alpha_j^* - 1)q_j^d > \sum_{i=n_1+1}^{n_2} q_i^d$.
The two assumptions imply that the aggregate PV capacities exceed the aggregate consumption of the n agents. The units injected to the microgrid and consumed locally will cost θ^l, the units exported to the central distribution network will cost θ^c.

The optimality constraint for A_j:

$$c\alpha_j^* q_j - (\alpha_j^* - 1)q_j(p^{FiT} - \theta^c) \leq cq_j \tag{14}$$

$$p^{FiT} \geq c + \theta^c \tag{15}$$

The optimality constraint for the system:

$$c\alpha_j q_j^d + (\alpha_j - 1)q_j^d \theta^c < cq_j + (\alpha_j - 1)q_j^d(g^d + \theta^c) \tag{16}$$

$$c < g^d \tag{17}$$

If n_1 agents invest in installations that exceeds the aggregate daytime consumption of the n agents, the extra units are sent to the central distribution network with a cost $\theta^c > \theta^l$. If $c < g^d$, the unit cost of the PV installation is very low so that it is efficient to invest $\alpha_j^* = \bar{\alpha}_j$.

All constraints are satisfied if:

$$p^{FiT^*} \leq g^d + \theta^c \tag{18}$$

$$p^{FiT^*} = g^d + \theta^c \tag{19}$$

Proposition 3 When $c < g^d$ and p^{FiT} is equal to the opportunity cost, the *first-best* is achieved when $\sum_j k_j \geq \sum_i q_i$, $j \subset i$. In such case, the investments of the agents generate positive externalities.

3.5 Scenario 3: Investments with negative externalities

We assume that: (i) $g^d < c < g^d + \theta^c - \theta^l$; (ii) $p^{FiT} = g^d + \theta^c$; and (iii) Equation (4) does not hold.

When the feed-in-tariff is equal to the opportunity cost, the n_1 agents will have an incentive to invest in the maximum PV capacity such that $\alpha_j = \bar{\alpha}_j$. The investments' of the agents are not efficient as there are over-investments, i.e., investments are above the local needs. More generally, we can show that there is no linear p^{FiT} that leads to the first-best investment level.

Proposition 4 When $g^d < c < g^d + \theta^c - \theta^l$ and p^{FiT} is equal to the opportunity cost, there will be over-investment in PV installations with $\sum_j k_j > \sum_i q_i$, $j \subset i$. The *first-best* is no longer achieved, and the investments of the agents generate negative externalities.

4 Restoring Efficiency with P2P

In this section, we consider the case where households' investments generate negative externalities. We extend the model, to allow for the possibility of local exchange between the neighbours. A P2P bilateral contract allows the peers to exchange energy within the microgrid. This contract will restore the local balance between supply and demand without the intervention of intermediaries. The contract has to specify the units of energy traded between the prosumers and the consumers, the price at wich the energy will be exchanged, as well as the timing of the exchange.

4.1 Local exchange when the feed-in-tariff is too low

We assume that the regulator sets a feed-in-tariff $p^{FiT^{**}} = g^d$. By doing so, he reduces the feed-in-tariff in order to discourage over-investment and to restore efficiency, i.e., a situation where $\sum_j k_j = \sum_i q_i^d$.
When the feed-in-tariff is equal $p^{FiT^{**}}$, the optimality constraint for the agents A_j, $j = 1, ..., n_1$, is no longer satisfied. Each agent will invest in a PV capacity that satisfies his auto-consumption. The n_2 neighbours will have to import their daytime energy from the central system.Both the n_1 prosumers and the n_2 consumers will be better-off if they sign a P2P contract.
The n_2 agents will buy the residual production of the n_1 prosumers: $Q^{P2P} = \sum_j (\alpha_j - 1) q_j^d$.
The optimal price have to maximize the surplus of both the prosumers and the consumers.

The optimality constraint for A_j:

$$c\alpha_j^* q_j - (\alpha_j^* - 1)q_j(p^l - \theta^l) \leq c\alpha_j^* q_j - (\alpha_j^* - 1)q_j(p^{FiT^{**}} - \theta^c) \quad (20)$$

$$p^l \geq g^d - (\theta^c - \theta^l) \quad (21)$$

The optimality constraint for A_i:

$$(\alpha_j^* - 1)q_j^d(p^l + \theta^c) \leq (\alpha_j^* - 1)q_j^d(g^d + \theta^c) \quad (22)$$

$$p^l \leq g^d \quad (23)$$

$$(24)$$

All constraints are satisfied if:

$$p^{l^*} \in \left[g^d - (\theta^c - \theta^l); g^d\right] \quad (25)$$

Proposition 5 When the feed-in-tariff is lower than the opportunity cost, the agents are better-off when they sign a P2P contract and locally trade the surplus energy generated at an agreed local price equal to p^{l^*}.

4.2 Local exchange under load shifting

In this section, we extend the model to allow for the possibility of load shifting.

The consumption of A_j, $j = 1, ..., n_1$, is q_j^d at daytime and q_j^n at nighttime. The consumption of A_i, $i = n_1 + 1, ..., n_2$, is $\underline{q_i^d}$ at daytime and $\bar{q}_i^n$ at nighttime. When A_j invests $\sum_j k_j > \sum_j q_j^d$ with $\alpha_j^* = \bar{\alpha}_j$, the supply and demand between the prosumers and the consumers is not longer balanced: $\sum_i \underline{q_i^d} < \sum_j (\bar{\alpha}_j - 1)q_j^d$, and the excess production of the PV installations is not consumed locally and is injected into the central grid. We assume that the n_2 consumers can shift some load of their nighttime consumption to daytime to reach $\bar{q}_i{}^d$, with a cost γ. In this case, the balance of the supply and demand between the prosumers and the consumers is restored, i.e., $\sum_i \bar{q}_i{}^d = \sum_j (\bar{\alpha}_j - 1)q_j^d$.

Without local bargaining, the first-best is not achieved. The agents have to find a local agreement that defines the level of investment of the prosumers, the quantity that will be exchanged and the local price that gives incentives to both parties, the prosumers to invest $\alpha_j = \bar{\alpha}_j$ and the consumers to shift loads to reach $\underline{q_i^d}$. In case of no contract, the n_1 prosumers will invest $k_j = q_j^d$ and the n_2 consumers will import their total energy needs from the central system.

The system optimality constraint:

$$c\alpha_j q_j^d + (\gamma + \theta^l)\Delta q_i^d \leq c q_j^d + (g^n + \theta^c)\Delta q_i^d \tag{26}$$

where $\Delta q_i^d = \bar{q_i}^d - \underline{q_i^d}$

$$c \leq (g^n - \gamma) + (\theta^c - \theta^l) \tag{27}$$

The optimality constraint for A_j:

$$c\alpha_j q_j^d - (\alpha_j - 1)q_j^d(p^l - \theta^l) \leq c q_j^d \tag{28}$$

$$p^l \geq c + \theta^l \tag{29}$$

Using (28) and (30):

$$g^n - \gamma + \theta^c - \theta^l \leq p^l - \theta^l \tag{30}$$

$$p^l \geq g^n + \theta^c - \gamma \tag{31}$$

The optimality constraint for A_i:

$$(\theta^l + p^l)\Delta q_i^d \leq (g^n + \theta^c)\Delta q_i^d \tag{32}$$

$$p^l \leq g^n + \theta^c - \theta^l \tag{33}$$

All constraints are satified if:

$$\theta^l < \gamma \tag{34}$$

and

$$p^{l^*} \in \left[g^n + \theta^c - \gamma; g^n + \theta^c - \theta^l\right] \tag{35}$$

Proposition 6 When $\theta^l < \gamma$, the first-best is achieved when the consumers shift their energy usage load and the prosumers invest $\alpha_j = \bar{\alpha}_j$ and they exchange energy at a local price p^{l^*}.

5 Conclusion

In this paper, we derived a model to demonstrate the conditions under which households'investments in PV installations are optimal. We showed that in case of negative investment externalities, P2P is necessary to restore efficiency.

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