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Article

Optimal Simulation of Three Peer to Peer (P2P) Business Models for Individual PV Prosumers in a Local Electricity Market Using Agent-Based Modelling

Marco Lovati [1], Xingxing Zhang [1,*], Pei Huang [1], Carl Olsmats [1] and Laura Maturi [2]

[1] School of Technology and Business Studies, Dalarna University, SE-79188 Falun, Sweden; mlov@du.se (M.L.); phn@du.se (P.H.); cos@du.se (C.O.)
[2] Renewable Energy Institute, EURAC, 39100 Bolzano, Italy; laura.maturi@eurac.edu
* Correspondence: xza@du.se

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Abstract: Solar photovoltaic (PV) is becoming one of the most significant renewable sources for positive energy district (PED) in Sweden. The lack of innovative business models and financing mechanisms are the main constraints for PV's deployment installed in local communities. This paper therefore proposes a peer-to-peer (P2P) business model for 48 individual building prosumers with PV installed in a Swedish community. It considers energy use behaviour, electricity/financial flows, ownerships and trading rules in a local electricity market. Different local electricity markets are designed and studied using agent-based modelling technique, with different energy demands, cost–benefit schemes and financial hypotheses for an optimal evaluation. This paper provides an early insight into a vast research space, i.e., the operation of an energy system through the constrained interaction of its constituting agents. The agents (48 households) show varying abilities in exploiting the common PV resource, as they achieve very heterogeneous self-sufficiency levels (from ca. 15% to 30%). The lack of demand side management suggests that social and lifestyle differences generate huge impacts on the ability to be self-sufficient with a shared, limited PV resource. Despite the differences in self-sufficiency, the sheer energy amount obtained from the shared PV correlates mainly with annual cumulative demand.

Keywords: microgrid; PV; peer to peer; self-consumption; energy community; local market

1. Introduction

1.1. Background and Literature Review

Positive energy districts (PED) are defined as energy-efficient and energy-flexible building areas with surplus renewable energy production and net zero greenhouse gas emissions [1]. Solar photovoltaic (PV) is ideally a leading renewable source in PEDs due to its easy scalability, simple installation and relatively low maintenance. Distributed PV systems are the main driver in the Swedish PV markets, due to smaller size and distributed ownership, which are better adapted to permeate the urban environment. The installed capacity of PV systems in Sweden is expected to continuously soar in the future, mainly driven by homeowners and private or public companies at relatively small or medium scales, according to its particular market setup and subsidy (e.g., SOLROT deduction, tax reduction, etc.) [2]. However, relying on the subsidy is not sustainable for PV deployment in the long term. At the moment, there is still limited access to capital and appropriate financing mechanisms, resulting in a slow uptake of PV under traditional business models (i.e., power purchase agreements and the net-metering mechanism), which are no longer applicable for small PV systems [3]. The existing business models may need to be further developed to exploit the full potentials generated by distributed energy supply, demand and energy sharing. Thus, in a future without subsidies, prosumers (i.e., small PV owners) will have to sell their excess production at market price back to the grid. This scenario would be unprofitable for PV owners and also strain grid stability and reduce its reliability.

Fortunately, the possibility to form energy communities, where energy can be locally shared, has been regulated at European level in the Clean Energy package presented by the European Commission [4] and at Swedish level under § 22 (a) of the IKN Regulation 2007: 215 [5]. This can be an opportunity for a new business model development within the energy sector, e.g., Peer-to-Peer (P2P) trading. In such business model, consumers and prosumers organise in energy communities, in which the excess production could be sold to other members [6]. The benefits are threefold as the prosumers could make an additional margin on their sale, consumers could buy electricity at a more advantageous price and the grid could be more stable and resilient. This can be a potential solution to promoting PV installation in a sustainable way, while reducing the reliance on subsidies.

To support new regulations, careful design and optimal modelling of P2P business models for PV penetration is necessary by analysing current scenarios and proposing future ways of exchanging energy. Huijben and Verbong [3] summarised three possible ownerships of PV systems: customer-owned (single ownership), community shares (multiple ownership) and third-party ownership. Based on these possibilities, Lettner et al. [7] further described three different system boundaries of a PV prosumer business concept (as illustrated in Figure 1): Group (1) single direct use (one consumer directly uses the generated PV electricity on site); Group (2) local collective use of PV in one building (several consumers share the generated PV electricity with or without the public grid); and Group (3) district power model (PVs are installed in several buildings, where those prosumers directly consume locally generated PV power and the PV electricity is further shared using public or private microgrid). It is possible to have different ownerships in each category of these boundary conditions, resulting in many possibilities and uncertainties in the practical business operation. Learning and mapping (i.e., testing) a wide array of these possible designs and combinations are necessary. There are a few existing regulatory and modelling studies about the P2P PV-electricity trading. Community-owned PV system was surveyed as an innovative business model in Switzerland, where it can seemingly be a successful distribution channel for the further adoption of PV [8]. Roberts et al. tested a range of financial scenarios in Australia, based on the P2P concept, to increase PV self-consumption and electricity self-efficiency by applying PVs to aggregated building loads [9]. Zhang et al. [10] established a four-layer system architecture of P2P energy trading (as shown in Figure 2, i.e., power grid layer, ICT layer, control layer and business layer), during which they focused on the bidding process on business layer using non-cooperative game theory in a microgrid with 10 peers. A price mechanism for the aggregated PV electricity exchange among peer buildings was also developed using either Lagrangian relaxation-based decentralised algorithm [11] or mixed integer linear programming [12]. Jing et al. [13] then applied the non-cooperative game theory to modelling the aggregated energy trading between residential and commercial buildings by considering fair energy pricing mechanism for both PV electricity and thermal energy simultaneously. Lüth et al. [14] designed two local markets for decentralised storage (flexi user market-individually owned batteries) and centralised storage (pool hub market-commonly owned battery), based on a multi-period linear programming. It focused on the evaluation of two different ownerships of batteries and optimised P2P energy trading local markets. They indicated that the end users can save up to 31% electricity bills in the Flexi User Market and 24% in Pool Hub Market. Furthermore, two different ownership structures, namely the third-party owned structure and the user owned structure, were investigated in a P2P energy sharing network with PV and battery storage [15]. These existing studies almost cover all four layers of a P2P network. The impact of other system and market components on the economic performance of PV P2P business models has been investigated, such as EV (Electric Vehicle) batteries [16], gas storage [17], heat pump/hot water storage [18], advanced control [19], energy cost optimisation [20], bidding strategies for local free market [21], double auction market [22], local market designs [23], integration of local electricity market into wholesale multi-market [24], microgrid ICT architecture [25], grid operation [26], etc.

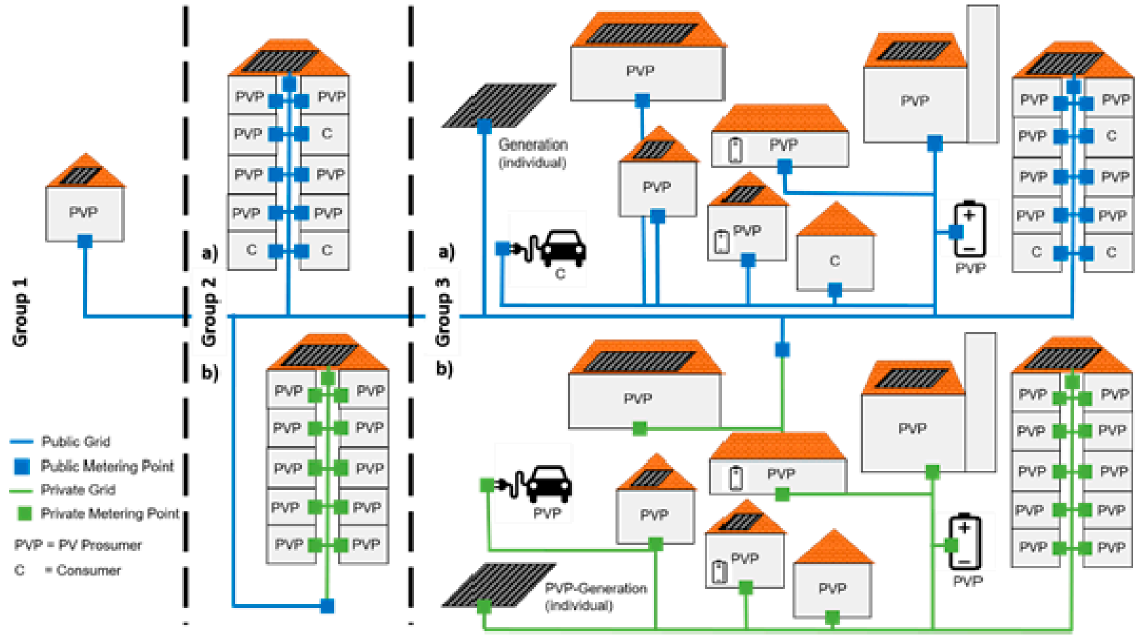


Figure 1. Classification of integration concepts [7].

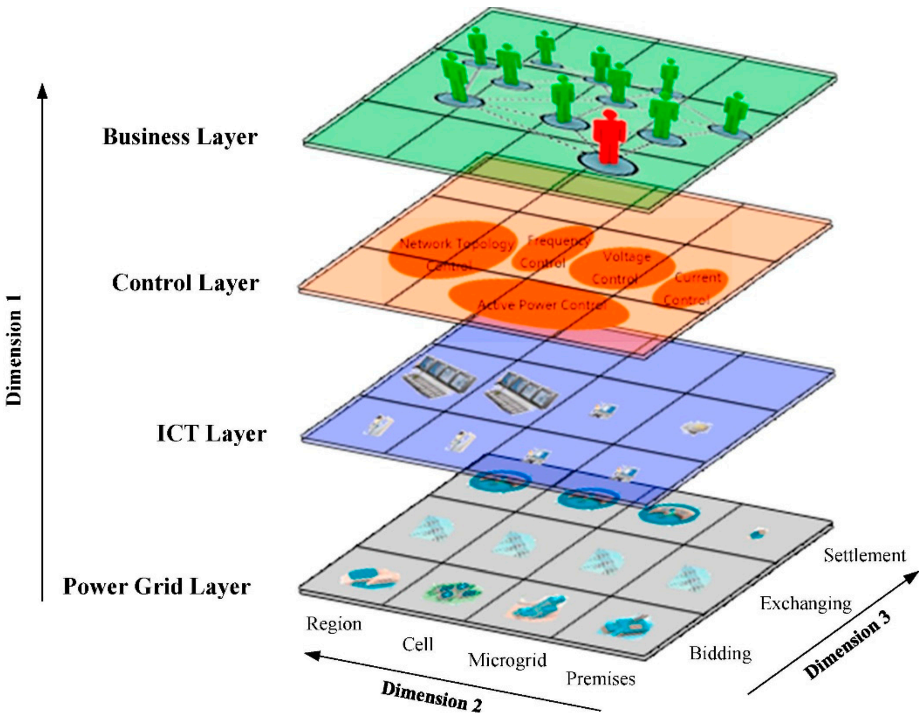


Figure 2. The four-layered system architecture of P2P energy trading from [10].

According to the above studies, a research gap is found in the lack of examination on full P2P energy trading process at the business layer in a local market for individual participant, which, in time sequence, consists of bidding, exchanging and settlement, under different local market conditions with various ownerships of PV systems and market rules. Bidding is often the first process when energy players (generators, consumers and prosumers) agree to trade energy with each other at a certain price for a specific amount of energy. Energy exchanging is the second process, during which energy is generated, transmitted and consumed. Settlement is the last process when bills and transactions are finally settled via settlement arrangements and payment [10], which results in the final economic benefits. In cases of the physical network constraints, due to the varying energy demand and the intermittent generation of PVs, there are always mismatches between sellers and buyers. Such difference between electricity generation and demand are to be evaluated and charged/discharged during settlement stage.

1.2. Novelty and Contribution

Several studies have focused on the technical or economic aspects of the microgrids and shared RES, but the endeavour has been tackled in a segmented way analysing a narrow sample of possibilities among the vast search space of the business models. The existing studies have not yet fully tested the effectiveness and compared the characteristics of various P2P business models, in the case of heterogeneous peer (individual) energy supply/demand and dynamic market rules for the full trading process on the business layer. There is a lack of a concise and efficient method yet to model.

Although this paper only analyses three different setups, it attempts to lay the groundwork for a systematic study of the subject. In other words, the results and the discussion presented in this paper, although not conclusive by themselves, are part of a well-defined search-space. This allows the outcomes to be interpreted from the perspective a larger systematic endeavour.

In summary, the elements of novelty of this paper are described as the following:

(1) The particular result of the study: To the knowledge of the authors, no study has linked the price of the electricity offered within a shared RES to both the risk of economic loss and the potentials for earning among the individual households within the shared microgrid. Furthermore, the dominance of shear annual cumulative consumption over self-sufficiency in determining the earning potential in a shared RES is an unknown phenomenon. It deserves to be further analysed (i.e., tested under different datasets) to be proven.

(2) The examples of business models presented in the study are included in a well-defined search space map (see Figure 3). This facilitates a systematic inquiry and offers a way to organise the results presented in this study and in the follow-ups.

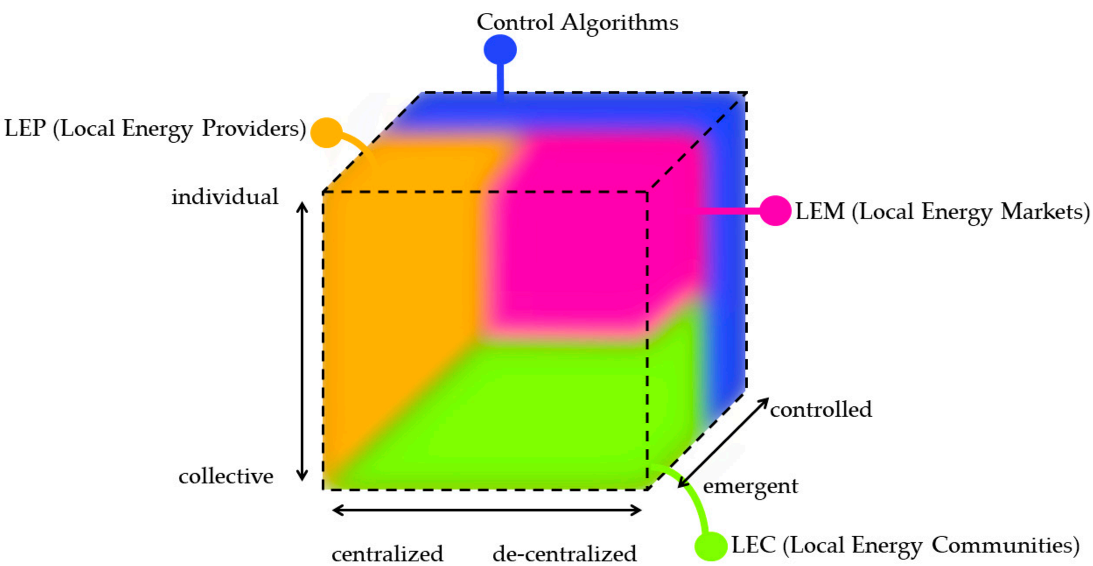


Figure 3. District scale renewable energy systems behaviour map.

This paper studies the P2P business model for 48 individual building prosumers with PV installed in a Swedish community. This paper discovers "latent opportunities" that were previously unknown and optimises the market design and its variables for the best benefit. It has significant influence that integrates energy needs, supply and market rules. This paper is expected to provide knowledge for policymakers to design a fair, effective and economical P2P energy framework. The research results will useful be to optimise PED's three functions (energy efficiency, energy production and flexibility) towards energy surplus and climate neutrality.

2. Materials and Methods

The definition of ownership structures from [3] distinguishes among customers, communities and third parties. In general, a similar distinction could be applied to the behaviour of the local grid instead to the ownership. In this way, the concept of ownership is not associated with the functioning of the grid and it is easier to describe hybrid forms (e.g., some shareholder of an energy provider, or more providers, which form a market although not prosumers). Thinking about the behaviour of the shared system, a space can be defined according to three dimensions (see Figure 3):

(1) The **controlled versus emergent** dimension describes how much there are rules or a controller that directs the exchanges, versus an emergent behaviour from the interactions between agents.
(2) The **centralised versus de-centralised** dimension describes how much the agents are equivalent among each other, versus the presence of few (potentially one) agents that concentrate some functions for a larger number of others.
(3) The **individual versus collective** dimension describes how much each agent controls and directs its own resources (i.e., PV, storage, demand-response resources, etc.), versus having larger pools of agents who share some common resources.

The behaviour map does not refer to any specific levels [10], although the last two (i.e., controls and business) are particularly affected from the volume of the map, in which they are located. In fact, the control of the energy and monetary flows between generation and demand points can be decided by a controller, which can be assigned by the internal rules of a community or emerged as the result of an auction.

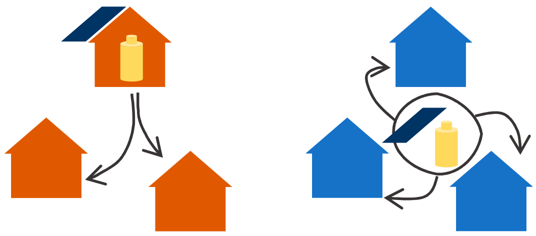
2.1. *Agent-Based Model*

Given the number and nature of the emergent behaviours in the behaviour map (i.e., Figure 3), an agent based model (ABM) simulation was developed to get insight into the energy and economic fluxes exchanged between the different actors in the local grid. Usually, every agent of the simulation represents one household in the local grid (i.e., a consumer or a prosumer), but producers are not excluded. An example of a producer is an energy provider. For instance, companies or investor interacts with the local grid without necessarily being served by it, or the parent grid, i.e., the larger grid in which the local grid is embedded. The local grid could be a microgrid but also a secondary network, where the prosumers are allowed to have a certain level of control of the network.

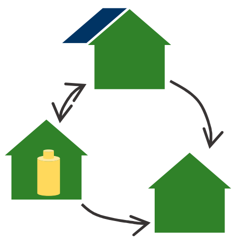
In an ABM, each agent can interact with all the other agents by trading energy. Thus, it can send energy in exchange for money or vice versa. The movement of energy in the microgrid is an emergent behaviour, which results from the interaction of a number of independent actors. This is opposed to a control algorithm, where the behaviour is set by a series of rules or conditions. Naturally, the freedom of the agents can be limited by the introduction of rules. For instance, a producer could be forced to prioritise the sale of renewable electricity to those consumers that have used the least of it in a given period. If the rules become tighter, the freedom of each individual agent is reduced. While if the rules are as tight as to completely limit any possibility of choice for the agents, the ABM degenerates into a control algorithm.

In the present study, the behaviour of the agents is extremely simplified: the consumers prioritise the purchase of electricity from the cheapest source available at any given time, on the other end the producers have the ability to set the price, and they do so according to the case as explained in the following section (i.e., ownership structures and business models). Figure 4 presents the possible ownership structures arranged into three main families; these are slightly different from those in [3] for the purpose of this study.

1. Local Energy Provider (LEP) (Figure 4a): It occurs when a single agent owns the totality of the production or storage capacity of the entire local network and the other agents are strictly consumers. The owner of the plant can be either a producer or a prosumer.
2. Local Energy Community (LEC) (Figure 4b): It is the case in which a communal plant is shared among all or a group of agents, the shares could be equally distributed or according to other principles such as energy used from the plant or the share of the initial investment.
3. Local Energy Market (LEM) (Figure 4c): It is the most complex and free-form of all the structures; it is characterised by the presence of multiple producers, consumers and prosumers. In this arrangement, the interaction between agents can reach significant complexity and the agents could achieve higher earnings by engaging in intelligent behaviours.



(**a**) (**b**)



(**c**)

Figure 4. Possible ownership structures organised in three main families: Local Energy Provider (LEP) (**a**); Local Energy Community (LEC) (**b**); and Local Energy Market (**c**).

2.2. Ownership Structures and Business Models

In the case study examined (see Section 2.3), a communal PV plant is shared among the different households in the building. This allows for two of the three basic ownership structures in Figure 4 (i.e., LEP and LEC) to be applied. The ownership structure is intertwined with the business model and the rules of the market. In the following studies, the same communal PV plant is shared between the households in the local grid in three different scenarios:

1. **LEC gratis:** In this arrangement, the electricity from the communal PV plant is given for free when available. All the households participate in the initial investment and in the Operation and Maintenance (O&M) costs of the plant according to equal shares.
2. **LEC LCOE:** In this arrangement, the electricity from the communal PV is given at production cost (i.e., without profit) and the revenues are divided among the shareholders. Although variable shares are possible, in this study, all the households are equal sharers in the LEC (i.e., initial investment and O&M costs, and the revenues are shared equally).

3. **LEP n%:** This arrangement is a pure form of LEP. Thus, the production plant is owned by a single provider who can set the price at its own will. Obviously, the provider cannot set the price higher than that of the parent grid (i.e., the average price for Swedish household consumer as assumed in Section 2.3) as the consumers retain the right to purchase electricity from the cheapest source. In this study, the provider sets the price as half-way between the minimum of the local LCOE and the maximum of the consumer price from the parent grid. More precisely, the provider sets a price at a percentage n so that n = 0 is the LCOE, n = 100 is the price offered by the parent grid and n = 50 is half-way. This set-up is valid under the assumption that the LCOE of the system is lower than the price of the electricity for the consumer. Of course, if this assumption does not hold true, the provider will not be able to charge above market price and will thus operate at the minimum loss.

In all arrangements, the consumer is programmed to buy electricity from the cheapest source. However, by having a single source in the local grid, the choice is only between the local source and the parent grid. This implies that the price of electricity in the local grid must be at any time below the Swedish consumer price. If the local production is absent or insufficient (i.e., local consumption > local production), the demand shall be covered partially or totally by the parent grid. If the local production is not sufficient, at a given point in time, to cover entirely the demand, all the households will be served equally in terms of percentage of their demands as shown in the system of relations in Equation (1).

$$\begin{cases} E_{local} = \eta \times D_{local} \\ E_{house} = \eta \times D_{house} \times \forall house \\ D_{local} = \sum D_{house} \end{cases} \quad (1)$$

where E_{local} and E_{house} are the amount of electricity available in a given time for the aggregated local grid and for a specific household, respectively. η is the self-sufficiency: a number between 0 and 1 that represents the share of the demand covered by locally produced electricity; note that it is the same globally and for each household. D_{local} and D_{house} represent the aggregated demand and the demand of each single household, respectively.

Equation (1) implies that having a larger consumption when the local electricity production is scarce guarantees access to a larger amount of local energy, although equal in percentage. Another consequence of the relation in (1) involves the price of the electricity for each household: the price results from the weighted average (weighted on energy) of the prices from the different sources of electricity purchased. In the specific case of this study, the price can be calculated with the relation Equation (2):

$$P_{house} = P_{local} \cdot \eta + P_{parent} \cdot (1 - \eta) \quad (2)$$

where P_{house}, P_{local} and P_{parent} represent the electricity price for the individual household, the price for the energy produced locally and the price for the energy bought from the parent grid, respectively. η is the self-sufficiency as defined for (1).

Considering that η is the same for every household in the local grid as shown in (1), Equation (2) implies that at any given time there is a unique price of the electricity within the local grid, which depends on the relation between the aggregated energy demand (D_{local}) and the aggregate energy production (E_{local}). Thus, the price for the electricity is solely function of the Hour of the Year (HOY) and is not a function of any given household.

2.3. Case Study

The agent based model is tested on a digital representation of a moderate size residential district (see Figure 5) equipped with a shared PV system + DC microgrid as described in [18]. The group of three buildings with three stories is located in Sunnansjö, Ludvika, Dalarna region, Sweden. The common PV system is formed by the arrays shown in Table 1. In total, there are three arrays on the roof and one on the southern façade (total 65.5 kWp).

Figure 5. Bird view of the small district in the case study [18].

Table 1. Characteristics of the shared PV system.

Block	Facing	Tilt (degree)	Capacity (kW$_p$)	Production (MWh)
B	South	18	28.4	22
C	East	18	15.9	10.4
A	West	18	15.9	10.3
A	South	90	5.3	3.4

The system capacity and the position of the arrays over the building resulted from an optimisation process, presented in [18], in order to maximise the self-sufficiency while maintaining a positive NPV over the lifetime. In this system, no electric storage was installed. The LCOE (Levelized Cost of Electricity) of the system was calculated to be about 0.83 SEK/kWh (0.077 €/kWh) under the following assumptions:

- Local initial price of the turn-key system without taxation: 10,000 SEK/kWp (935 €/kWp).
- Price of the inverter: 2500 SEK/kWp (234 €/kWp) (changed two times over the lifetime). The number of changes was retrieved as the expected value assuming a lifetime of the inverter between 12 and 15 years.
- Planned lifetime of the system: 30 years.
- Maintenance costs for the system (substitutions, cleaning and inspection): 5109 SEK/year (477 €/year). This value was calculated as the expected value out of 100 stochastic simulations.
- Degradation of the performance of the system: ca. −1.15%/year.

The weather file and the production of the diverse arrays of PV were calculated from PVGIS [27]. The load profile of the 48 households could not be published for privacy concerns. Thus, the study is presented using data generated by LPG (Load Profile Generator) software [28]. Load Profile Generator is a tool that simulates the electric demand for residential light and appliances. The variability of the aggregated curve according to the number of households has been validated against a real low voltage grid consumption [29]. The electric demand is generated by simulating every household component as an agent. Its demand is determined by the power absorption and duration of use of devices among an available selection (see Figure 6). These are chosen by the household components according to a set of activities and needs. The needs are modelled as counters that grow at each time-step: a high counter represents something that is in urgent need of satisfaction. Different needs have different growth rates for each time step, which means that some needs are to be satisfied more often than others.

The parent grid (i.e., the Swedish national grid) was assumed to offer electricity for 1.8 SEK/kWh (0.17 €/kWh) from October to March and 1.2 SEK/kWh (0.11 €/kWh) from March to October. These prices were assumed as a reasonable price for each single household at the annual cumulative level of consumption observed. According to Eurostat (2007–2019), the average price for household electricity in 2019 was 1.39 SEK/kWh (0.1297 €/kWh) for electricity transmission, system services, distribution and other necessary services. If VAT and levies are added, the average price would reach 2.2 SEK/kWh (0.2058 €/kWh) (Eurostat, 2007–2019). It is not clear what taxes can be avoided consuming locally produced electricity, but it is reasonable to believe that VAT can be avoided in both the LEC cases explored as the electricity is offered for free or at a price equal to production cost. Conversely, it is not possible to estimate how much of the base 1.39 SEK can be reduced thanks to the aggregation of the loads. The price of the electricity is not static but is projected to grow linearly over the next 30 years at a rate of +1%/year. This is under the assumption that the national grid will need liquidity to invest in the energy transition. Conversely, the revenues for the energy sold to the grid are set to be worth 0.3 SEK/kWh (0.028 €/kWh), but are assumed to shrink by 1.67%/year under the assumption that the increase in installation of PV will gradually discount the energy during sunny hours.

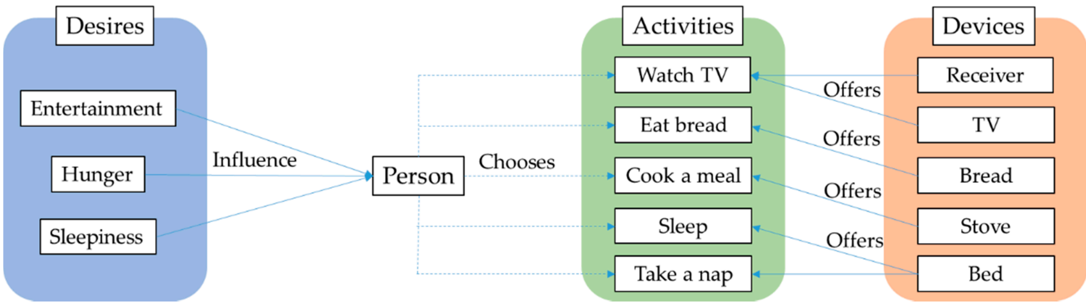


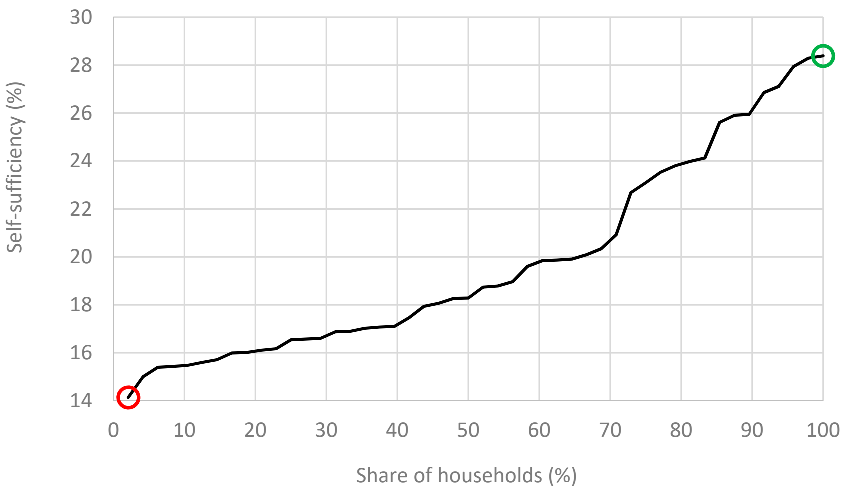
Figure 6. Workflow diagram of the load electricity generation [28].

3. Results

This section begins with a discussion about the self-sufficiency of the different households in the local network. It then proceeds with a techno-economic analysis of each arrangement to establish its features and behaviour (i.e., distribution of risk and profit among stakeholders). Given that the local PV plant is unique, the movement of energy in the network is the same in all the arrangements, thus the self-sufficiency is a static figure throughout the arrangements.

3.1. Self-Sufficiency of the Households

PV self-sufficiency is defined as the share of total demand in a household that is being supplied by locally generated electricity from PV system [30]. In this study, the system, as it is designed, allows to cover an estimated 20.2% of the annual cumulative demand of the district. This result is satisfactory for a system without any electric storage (see [31]). The country, with the most electricity production from PV (i.e., Honduras), has an estimate PV self-sufficiency of 14.8% with the EU on average having 4.9%. It has been calculated in references [32] and [18] that the economically optimal self-sufficiency of a conveniently aggregated system, even in absence of electric storage, is comfortably above any penetration level we see today (i.e., often above 20%). The economically optimal self-sufficiency sets a conservative limit of hosting capacity in an electrical system in a regime of self-sufficiency. The P50 (i.e., 50th percentile or median) household has a self-sufficiency of 18.5% as shown in Figure 7a: this value is below the average value of the aggregated district because the slope of the increase is higher to the right of P50 (see Figure 7a). The P50 household has a relatively low self-sufficiency because there is a positive correlation between annual cumulative demand and self-sufficiency (see discussion about Figure 8). In general, the variability in self-sufficiency between the households in the microgrid is high. The most self-sufficient household possesses in fact a value double of the lesser one (14.1% to 28.4%). This strong variability suggests that, even without any deliberate attempt for demand control, some households show habits, or a way of life, that can take the most from the available PV energy.



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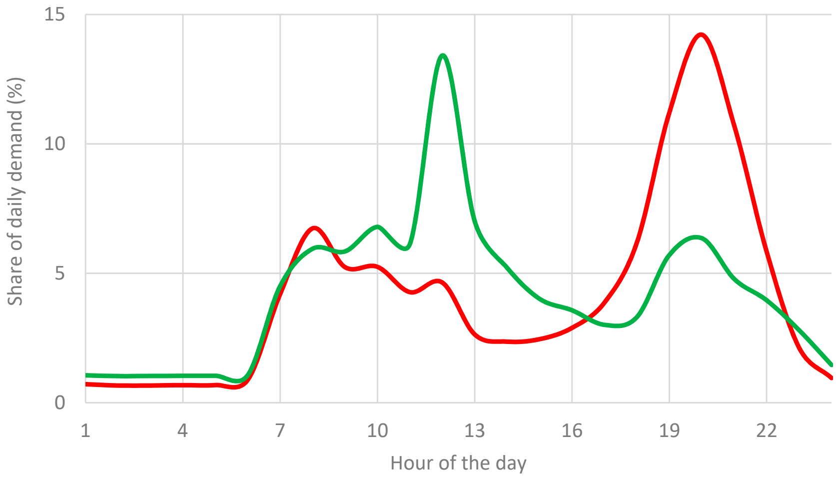

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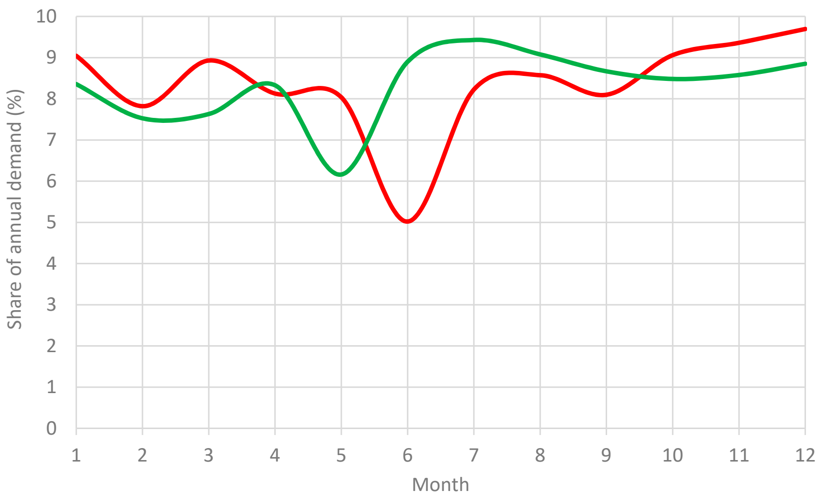
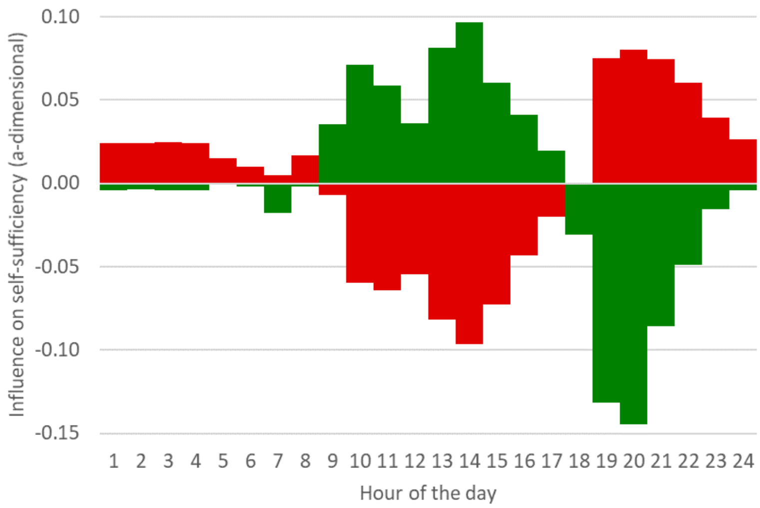


(**c**)

Figure 7. Self-sufficiency of the apartments in the local grid: (**a**) the distribution of self-sufficiencies across the 48 households; (**b**) the hourly average of the extreme households; and (**c**) the monthly average consumption of the extreme households.



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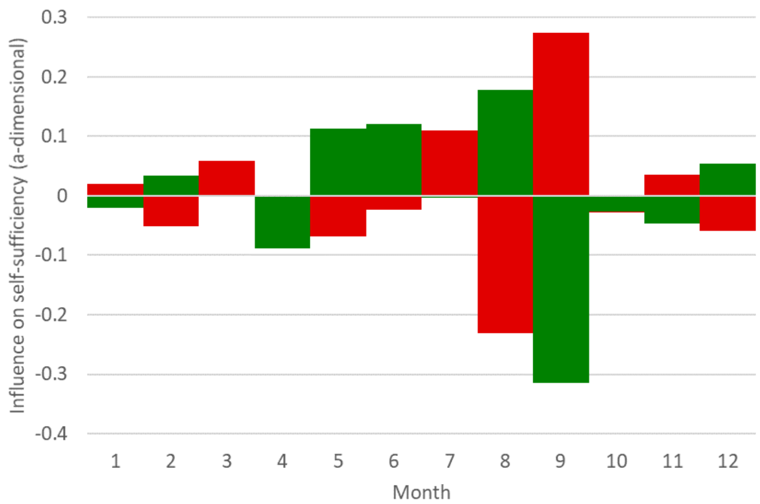


(**b**)

Figure 8. Influence on self-sufficiency of high demand in: (**a**) each hour of an average day; and (**b**) each month of the year. The value is a-dimensional but it expresses the positive (or negative) influence of a high electric demand at a given time step compared to all the others (see Equation (3)).

Figure 7b,c shows the share of the annual demand in different hours of the day or month of the year, respectively, i.e., how much of the total annual demand is concentrated during a specific hour of every day or month along the year. In the household with the highest self-sufficiency, the electricity demand around 12:00 is particularly prevalent (see Figure 7b). It indicates that its inhabitants cook at home for lunch. On the other end, the evening peak of the most self-sufficient household is way less prominent than in the lowest one. Looking at the prevalence throughout the months of the year (Figure 7c), the difference is less marked compared to the daily average: both households present a steep drop in sunny months, which seems to indicate an absence due to summer holidays. The most self-sufficient household appears to have had an absence for holidays during May instead of June, as shown in Figure 7c. This might be advantageous as it allows to use more PV electricity when the overall electricity demand of the district is lower and the radiation from the sun is higher. It should be noted that, in general, the best performing household presents a smaller dip in demand for the summer holidays; it is unknown whether it is due to a shorter holiday or the presence of some household components at home.

The examples shown in Figure 7 highlight the two apartments that are extreme in terms of self-sufficiency. To infer more generalised information on the time of high consumption that favours high self-sufficiency (see Figure 8) the following formula was used:

$$ISelfS_{time\ step} = \sum_{HH=1}^{48} \begin{cases} TP_{time\ step,HH} - TP_{time\ step,\ tot} & \forall\ SelfS_{HH} > SelfS_{tot} \\ 0 & \forall\ SelfS_{HH} \leq SelfS_{tot} \end{cases} \tag{3}$$

where $ISelfS_{time\ step}$ is the influence of high energy demand in a given time step (which could be an hour of the day or a month of the year). *HH* stands for Household as the curve results from the sum of all the individual households. $TP_{time\ step,\ \mathbf{HH}}$ and $TP_{time\ step,\ tot}$ are the typical power demand (W) of said time step for the nth household (*HH*) and the whole district (tot), respectively. The sum of all time steps is then rescaled so that it is equal to 1.

In practice, the curve is influenced only by the households that have a self-sufficiency above average. It represents the influence (positive or negative) that the demand in each time step has on the overall self-sufficiency. Unsurprisingly, Figure 8a shows that a lower average demand in the evening and early morning hours is associated with high self-sufficiency. On the contrary, the central hours of the day are generally above average in highly self-sufficient households. It is interesting to notice how the electric demand at 12:00 is in general less beneficial for self-sufficiency than the hours around it: this is somewhat counterintuitive, but it makes sense since at 12:00 the high general consumption due to lunch causes scarcity of renewable energy more often than in the hours immediately before or after. The signal on a monthly basis is not so easy to interpret. It appears to be beneficial to have above-average consumption in August and below-average in September: this is possibly due to a fraction of the households that went on holiday later in any given year. Given the sharp drop in irradiation in the month of September compared to July and August, it seems reasonable that going on holiday in September increases the self-sufficiency over the year.

3.2. *Exploitation of the Common Renewable Resources: Sheer Cumulative Consumption Versus Self-Sufficiency*

Figure 9 shows the relation between the annual cumulative demand and the annual cumulative energy received from the shared PV system. These two variables are strongly correlated (R > 0.9); thus, the quantity of energy consumed from the PV system can be assumed with good confidence from the annual cumulative demand alone (i.e., regardless of the self-sufficiency).

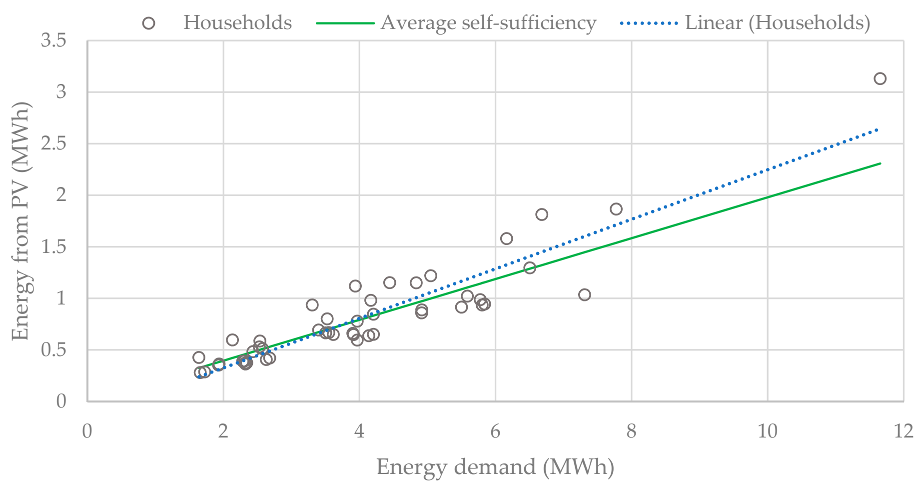


Figure 9. Annual cumulative energy demand and annual cumulative energy used from the PV system for every household in the local grid.

This aspect, although counterintuitive, is a consequence of the highest variability in annual cumulative demand compared to the variability in self-sufficiency: if in fact the highest self-sufficiency is two times the lowest one, the highest cumulative demand is almost five times the lowest one (excluding the highest value as an outlier; otherwise, it is more than seven times). The strong prominence in variability of cumulative demand compared to self-sufficiency reduces the variation in self-sufficiency as a mere noise compared to the other variable (as visible in Figure 9). Furthermore, as self-sufficiency is a share of the demand, it does not have much importance in absolute terms when applied to households with low cumulative demand. This fact represents somewhat a hindrance as it implies that increasing overall consumption works better than improving self-sufficiency to seize larger quantities of scarce local renewable resources. Nevertheless, it is not clear what power an individual household has to change its cumulative energy demand. Further investigation on the aspects that influence the cumulative energy demand (e.g., number of people in the household, cooking habits, holiday habits, etc.) is needed to assess whether it is something that the inhabitants can change. If each household has significant power on the cumulative energy consumption, it is reasonable to fear a sharp increase in the overall consumption after the installation of the communal PV system. It should be acknowledged that the lack of data with respect to other households might focus the attention of the inhabitants on their own energy demand advising them to increase the self-sufficiency. Another interesting aspect, shown in Figure 9, is that the linear interpolation of the household data points has a steeper slope than the average self-sufficiency of the 48 households. This means that the household with the highest annual cumulative consumption also has, on average, a highest self-sufficiency. The highest slope of the interpolation implies that at low consumption the self-sufficiency of a household tends to be lower than average, while at higher consumption tends to be higher. A correlation analysis between annual cumulative consumption and self-sufficiency found a positive, albeit weak, correlation ($R \approx 0.2$). Although it is weak and thus uncertain, the correlation suggests that highly consuming households might have more contemporaneity with the production from PV. This might be due to larger households having some members who stay at home during daytime, or to electric consumption by people who spend daytime at home being larger overall.

3.3. LEC Gratis

In this arrangement, the households in the district are shareholders of the system. Thus, they can use the electricity produced by the system for free when available. In this study, the shares of the PV system are equal. Each household will therefore have to pay 13,646 SEK (1275 €) of initial investment plus ca. 342 SEK/year (32 €/year) for maintenance and substitution of the inverter. Different ownership structures are possible, but the business model should be modified to avoid loopholes in the risk–benefit balance. For instance, equal shares could be distributed to a sub-group of the households (i.e., there are consumers who do not hold shares). In this case, an electricity price for non-owners should be established (see Section 2.2 LEP n%).

Figure 10 shows the difference in price between the energy offered by the parent grid and the energy available within the local system. The chart shows monthly values, which refer to the average cost of the electricity that month in the grid. We know from the Section 2.1 "Ownership structures and business models" that at any given time the price of the electricity is unique within the microgrid and depends on the relationship between production of PV and demand (see Equations (1) and (2)). The bars in Figure 10 are the average of all electricity prices of the respective month weighted by the aggregated electric consumption in that month. Obviously, since the energy not met by the local production is bought from the parent-grid, the external price has an influence on the internal one. In simpler terms, the internal price of the electric energy in one month, according to Equation (2) with Plocal = 0, is proportional to the residual demand. Notice that, due to the higher external price, the drop in cost of electricity during the months of March (Month 3) is similar to that in April (Month 4) despite a lower self-sufficiency.

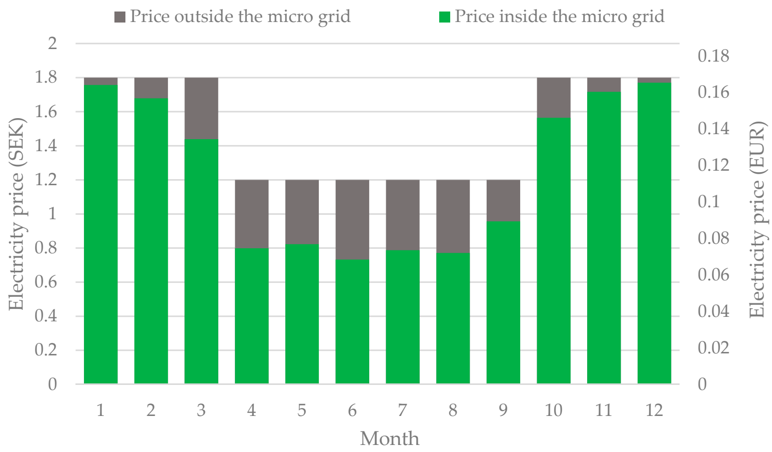
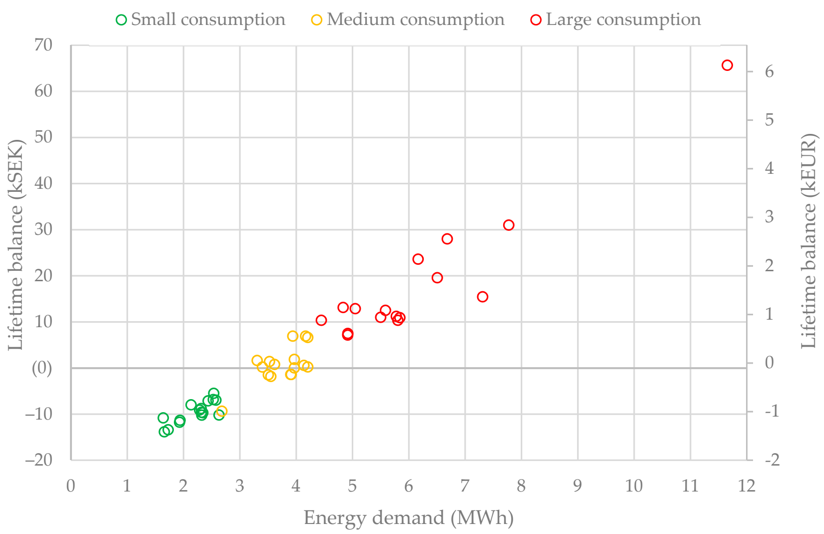


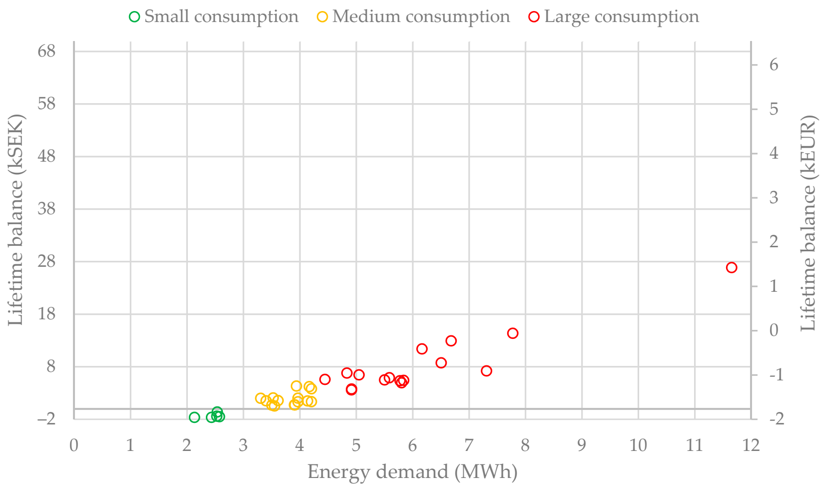
Figure 10. Monthly difference in price between the energy offered by the parent grid and the average paid by the shareholders in a LEC gratis arrangement.

Even if the price of the electricity is the same within the microgrid at any given point in time, the average price paid by each household varies according to the time patterns of consumption. A household will enjoy a lower average price when they consumed a large share of its annual consumption at times when the electricity was free (or at least cheaper). This is to say, a higher self-sufficiency will lower the average price. However, in terms of gross economic benefit (i.e., the sum that can be saved), it is not the average price that matters but the cumulative energy received for free. In this sense, the conclusion from the results in Figure 9 is troublesome as the earnings are not due to the ability to obtain a higher self-sufficiency but simply to the sheer cumulative consumption. In Figure 11, the households in the microgrid are divided into three groups of 16 elements each according to their annual cumulative consumption. As in Figure 9, the correlation of the KPI (Key Performance Indicator) with annual cumulative consumption is evident. In fact, the lifetime economic balance is determined solely by the savings, thus by the sheer quantity of energy that is received by each household. In Figure 11a, it is visible how being in the upper third of the cumulative consumption charts guarantees substantial earnings (IRR: internal rate of return from 1.9% to 6%), in the case of the initial investment about 13,646 SEK (1275 €/household). Conversely, the low-consumption households are doomed to economic losses, which means they are unable to recover the investment itself.



(a)

Figure 11. *Cont.*



(b)

Figure 11. Cumulative balance over the lifetime of the system against the annual energy demand. The households have been divided in three groups, each of 16 specimens, according to their cumulative consumption: (**a**) LEC Gratis; and (**b**) LEC LCOE.

If the relation between annual cumulative consumption and lifetime earnings would become known by the households in the local grid, there is a risk that there would be a considerable increase of the cumulative demand after the installation of the communal system. This fact, although potentially reducing the risk for those investing in the system (especially in a LEP case), would counteract the purpose of reducing consumption of electricity from the grid.

3.4. LCOE of LEC

If the energy is sold at production cost (LCOE), instead of being given for free, the difference in lifetime balance from the different households are greatly reduced, but they persist. In this case, the advantage associated with the use of energy from the system is influenced by the stake of ownership of the system. In general, it can be noted that the lifetime earnings (i.e., Figure 11a,b) follow a linear transformation from the extreme inequality (as in Figure 11a), to a situation of complete equality of earnings (if a LEC grid-price is hypothesised), where no benefit is obtained by the use of on-site electricity. In the hypothesis, a benefit for self-consumed electricity would spur increased self-sufficiency. A balance should be found between risk for the low consumption households and reward for the consumption of local renewable energy.

3.5. LEP N%

In this arrangement, the PV system is owned by a single provider who has the right to set the price. Obviously, since the parent grid can supply 100% of the demand of the district, the owner cannot set the price higher than the electric grid lest being completely out-bid (e.g., no household would use the owner's energy). In this study, the provider sets the price as half-way between the minimum of the local LCOE and the maximum of the consumer price from the parent grid. More precisely, the provider sets a price at a percentage n so that n = 0 is the LCOE, n = 100 is the price offered by the parent grid and n = 50 is exactly half-way in between.

Table 2 shows how the annual revenues, the balance over the lifetime and the real IRR change according to the price at which the electricity is sold.

Table 2. Annual revenues, lifetime balance and Internal Rate of Return (real) of the investment by different prices set by the owner.

N (%)	Revenues (SEK)	Balance (SEK)	Balance (€)	IRR (%)
0	34,553	−94,058	−8790	−0.5
9.43	37,689	0	0	0.0
25	42,864	155,247	14,509	0.7
50	51,174	404,553	37,809	1.6
75	59,484	653,859	61,108	2.3
100	67,794	903,165	84,408	2.9

Notice how with n = 0% (i.e., the electricity sold at production cost of 0.83 SEK/kWh), the balance and thus the IRR result are negative. This is because the self-consumption of the system is not 100% (it is in fact ca. 85%). In other words, not all the energy produced by the PV system is consumed by the households in the local grid. Therefore, part of the production is sold to the grid below LCOE and results in a moderate loss over the lifetime. The existence of this loss justifies the use of a LCOE adjusted for self-consumption, as described in [18]. This loss also explains why, under LEC LCOE arrangement, some households experience economic losses over the lifetime when the electricity by the communal system is given at price of cost (see Figure 11b). When the electricity is sold at LCOE, the IRR of the PV system is negative, thus holding its shares leads to a loss unless the benefit for cheaper energy outweighs the costs.

Applying an n = 9.43% does not result in any loss or gain over the lifetime of the system. It can be argued that no investor would like to take any risk to have an expected NPV (Net Present Value) of 0 at the end of the lifetime with a discount rate of 0. Nevertheless, there are potential business models for large homeowners such as general contractors or municipalities who could substitute part of the roof and façade cladding with BIPV thus avoiding the cost of an alternative material. Furthermore, this price tag is extremely interesting as price of sale from LEC. It in fact presents the advantage of expected lifetime economic balance in positive ground for each household.

A good business opportunity is finally offered by the n = 100%. This price, while suggesting a real IRR around 3% for the LEP, offers the occupants the opportunity to largely increase their share of renewable energy use without having to pay any upfront cost. In this case, the households have no economic benefit in installing the PV, but they have no risk or upfront investment and could receive information about their own self-sufficiency by the provider, e.g., with a monthly email.

4. Discussion

4.1. Social and Cultural Differences among Households Have a Huge Impact on Self-Sufficiency

In the local grid, if the renewable energy is not enough to cover the electric demand during a specific hour, the aggregated self-sufficiency is assigned to each household regardless of its demand (see Equations (1) and (2)). A large difference in terms of self-sufficiency has been observed within the 48 households, with the individual self-sufficiencies spanning from ca. 14% to more than 28% (see Figure 7a). Considering the absence of active strategies to increase the self-sufficiency in the cluster, such large differences can be attributed only to socio-cultural factors and spontaneous lifestyle choices. In Figure 7b, it appears that the most self-sufficient household has on average the peak of energy consumption at noon (possibly due to home cooking), while the least self-sufficient one has usually its peak consumption at 20:00. Differences are visible also over the different months of the year but their effect is not as clear as in the hours of the day. The large differences observed in self-sufficiency, having no active engagement or use of demand-shifting technologies, invites a deeper analysis and understanding of the existing electric demand and the factors which affect self-sufficiency.

4.2. High Cumulative Energy Demand Is More Effective Than High Self-Sufficiency in Exploiting the Shared Renewable Resource

Despite the large variation in self-sufficiency, it has been observed that the sheer amount of energy used from the system is mainly determined by the annual cumulative demand (see Figure 9). This phenomenon, albeit counterintuitive, is due to the fact that the variability of cumulative demand far outweighs the variability in self-sufficiency (the largest being five or even seven times the smallest one). In other words, the fraction self-consumed is not significant when applied to a group of households whose entire demand is hardly significant compared to others. This fact is problematic because the energy savings (i.e., the main earning mechanism of the investment in some market designs) come from the amount of PV energy consumed and not from the self-sufficiency reached. The relation between annual cumulative consumption and cumulative energy from PV is transposed in the relation between energy consumption and lifetime balance (see Figure 11). The balance in a LEC gratis arrangement (Figure 11a) is almost completely determined by the cumulative consumption, with the self-sufficiency being reduced to a noise in the linear relation. Moreover, if the households are divided into three groups according to their cumulative consumption, the biggest consumers all have positive balance and the smallest consumers all have a negative one. This aspect suggests that, if the communal PV system is installed under a LEC gratis arrangement, the shareholders might increase their electric demand in a bid to outdo each other's energy consumption. This behaviour would possibly defeat the purpose of installing on-site renewables in the first place. It should also be considered that, due to privacy laws and standard practice, each individual household is likely only aware of its own electric demand and self-sufficiency. This lack of data might drive each household to work on improving self-sufficiency instead of annual cumulative demand. It should also be remembered that the earnings are savings, thus increasing the cumulative demand would lead to an increase in the energy bill. In this sense, the increased exploitation of the common electricity through increased cumulative demand would happen only if increased consumption is perceived as a value, for example through the purchase or increased use of energy hungry appliances for cooking or DIY (Do It Yourself) purposes. How easy or difficult it is to change self-sufficiency compared to cumulative demand should also be considered to assess the likelihood of one scenario over the other. For example, cumulative demand might be strongly constrained by working schedule or number of household members. These aspects reiterate the need for a deeper study on the aspect of demand that influence self-sufficiency. From the perspective of the investment in PV, both the changes in behaviour envisioned would increase self-consumption, hence earning potential.

4.3. Different Selling Prices Generates Various Business Opportunities

Assuming that the shared PV system is owned by a single entity in a LEP (Local Energy Provider) arrangement, this entity enjoys freedom in setting the price for the sale of electricity. This freedom is nevertheless constrained by the LCOE of the PV system and by the price offered by the parent grid. If the LEP sells electricity at a higher price than the parent-grid it will have no purchaser among the households. This happens because the grid has the capacity to satisfy 100% of the demand of the whole district at any time. For this reason, a coefficient "n" has been devised so that: $n = 0$ is the LCOE of the local system and $n = 100$ is the sale of energy at the exact same price as from the parent grid. It has been shown that at $n = 0$, despite selling at production cost, the lifetime balance is < 0. This is due to the self-consumption being below 100% (i.e., ca 85%), hence ca. 15% of the energy produced being sold at spot price (i.e., 0.3–0.15 SEK/kWh or 3–1.5 € cent/kWh). This loss also explains why in the LEC LCOE arrangement some households still have a negative lifetime balance, as demonstrated in Figure 11b. Another interesting selling price is the one obtained with $n = 9.43\%$ because this is the price at which no profit or loss is made from the LEP. This price tag, albeit unattractive as an investment for a third-party PV owner, presents an interesting way for building owners to substitute other claddings on their properties. Using this selling price offers in fact a building material that, contrary to every other, does not cost anything over its lifetime. If applied as common price in a LEC it allows all households to have a positive lifetime economic balance, yet to have individual differences in earnings. It should be said that this price was determined at the end of a previous run when the overall self-consumption was already known. In a real case, to obtain such an equilibrium, the price should be updated at any point in time according to the evolution of self-consumption and energy prices. Selling energy at the price of the parent grid (n = 100) could be an interesting investment as it guarantees the LEP with a real IRR of around 3%; it provides no economic benefits for the household consumers, but it gives them the ability to boost their reliance on renewable without any upfront cost or risk. Furthermore, the possibility for the households to buy voluntarily sized shares of the LEP could kick start a set of tantalising business opportunities.

5. Conclusions

In the study, a newly developed agent-based model was tested on a shared PV system serving a small district comprising 48 apartments in a local community. Different ownership structures were explored. The LEC arrangement was studied both with the electricity given for free to all the equal shareholders or given at a price (in the study the LCOE). For the LEP, because the free offering would make no sense, an array of different prices was tried (see Table 2).

5.1. Key Findings

The main findings of the study are reported as follows and interpreted in the corresponding paragraphs in the discussion Section 4:

- **Social and cultural differences among households have a huge impact on self-sufficiency:** The households were simulated without introducing any demand-response measure or smart control. However, some households achieved a self-sufficiency of almost 30% using the common PV system while others stopped short of 15%.
- **High cumulative energy demand is more effective than high self-sufficiency in exploiting the shared renewable resource:** Despite the large differences observed in self-sufficiency among households, the quantity of energy received from the shared system has been determined almost completely by the annual cumulative demand rather than by self-sufficiency.
- **Different selling prices generates various business opportunities:** Different value of n%, as defined in Section 2.2, generate advantage and interesting features for diverse stakeholders. For instance, a very low n% (i.e., <10%) generates a strong drive for the shareholders to self-consume as much PV energy as possible, but it contains a risk for the least consuming ones. Higher n% (i.e., from ca. 10% to 100%) are interesting for building owners and BIPV solutions and, amid increasing n%, become more and more interesting for third party energy providers.

5.2. Follow-Up Studies

The present study shows a plain set-up and a narrow set of possibilities, but it sets the stage for a broader class of studies. In principle, some of the simplifying assumptions employed in this study should be removed in favour of a higher realism and a more complex modelling; nevertheless, models that are too complex for the level of uncertainty and for the input data available should be avoided.

For instance, it is tempting to change the present model for the prices from the parent grid (i.e., static seasonal price and long-term linear trends for sold and bought electricity) into a spot-price with distribution costs. However, while the change reflects reality better, the long-term modelling of the spot-price would be a daunting task and affected by huge uncertainty. Thus, it might pay off to just maintain a simplified model for the prices (i.e., two seasonal prices for purchase and sale and time of day variation), but to perform a stochastic simulation with variability in the time-evolution of the prices. In other words, any further complexity addition should only be determined by the use case of the model. Furthermore, for this model, the use case is the market design to finance and maintain a fair and remunerative local electric energy system.

On the other end, there are several low hanging fruits that can be easily harvested: for example, while in this study the price was always set by a unique actor (be it a community or a provider), it would be interesting to explore the effect of different prosumer setting each an arbitrary price and explore their interaction. In this sense, one more step could be to endow the agents with some level of intelligence and let them adjust the price reacting to the environment to maximise potential economic gains.

In the present study, there are devices and loads that have not been investigated, such as EVs and electric storages, in the local grid. These features, given a simplified enough model, are extremely easy to be implemented and can constitute a game-changer in the effectiveness of a business model.

Another interesting and potentially prolific research direction would be the study of the demand itself. Given the large variation of self-sufficiency found among the different agents participating in the microgrid, it is possible to find correlation with socioeconomic and lifestyle parameters such as median age, work–home schedules, number of members in an household, etc. This does not constitute information in itself, but it can lead to different results according to the different shared renewable systems. In other words, each social mix might demand a different system (capacity of PV capacity of electric storage).

Regarding the demand, it is of paramount importance to consider how often a house remains vacant due to change or death of the owner. These aspects should be investigated in terms of impact over each business model, but also in terms of risk-mitigating effect of larger local grids. It shall not be forgotten that lower risk can allow lower IRR for the investment, thus unlock wider market niches. The vacancy of the households is also affected by socioeconomic parameters and median age of the households; these aspects likely present spatial variability in different parts of the city and the world.

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