



Local Energy Communities: Market Design Evaluation Using Agent Based Modelling

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Abstract

Solar photovoltaic (PV) is becoming one of the most significant renewable sources for positive energy district (PED) in most countries, including Sweden. The lack of innovative business models and financing mechanisms are one of the main constraints for PV's deployment installed in local community. This chapter therefore analyses a set of 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 chapter 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

Agent based modelling · Micro-grid · Self-sufficiency · Emergent systems · Prosumer · PV optimization

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17.1 Introduction

Climate change is one of the main challenges that threaten the well being or the very existence of human society. This threat cannot be ignored because it can impact a wide range of natural ecosystems and socio-technical systems. In the last few decades numerous technologies have been discovered, or improved, that can dramatically reduce our greenhouse gas emissions: renewable or low carbon energy generation devices, energy storage systems, energy

efficiency, and carbon capture devices. The vast majority of countries and international institutions on the planet agree on the danger of climate change and on the need for action (Liu et al. 2020). In other words, since the political and social will to build a low carbon economy has been largely achieved, the focus in this chapter has been put chiefly on practical strategies and effective transition pathways. The subject is how to achieve a transition to a low carbon society in an economically beneficial way and without causing discontent.

17.1.1 How Change Can Happen

To transform the will for change in actual change, it is important to understand the causes and the mechanisms that activate change. In Giddens (1984) an important role in the evolution of technology is played by the interaction between socio-technical regimes, I.e. the existing dominating technology and the social structure it generated, and technological niches, I.e. newer, smaller and dynamic socio-technical entities that disturb the existing regime. In Geels and Schot (2007) the authors elaborate different transition pathways (I.e. transformation, reconfiguration, technological substitution, and de-alignment and re-alignment) elaborating upon previous work and criticisms. In particular (Geels 2002) is reported, which add new elements on the subject introducing the so called ‘socio-technical landscape’. The socio-technical landscape is the sum of morals, beliefs, knowledge and ideas that can push the change in a socio-technical regime. In Suarez and Oliva (2005) different modifications of the socio-technical landscape are presented (I. e. regular, hyperturbulence, specific shock, disruptive, avalanche). Also (Scott 2013) speaks about the forces that drive a transition or the conservation of a socio-technical regime, which can therefore be seen as a socio-technical landscape. These forces are divided into three groups: regulative (e.g. laws and standards), normative (e.g. values and norms), and cognitive (such as beliefs and search heuristics). The study argues that the stronger of these forces is the cognitive

one since is the most immersive and invisible for the actors under its influence. Other aspects that are fundamental in a transition are the selection pressure and the coordination of resources, these two are deeply interconnected according to Smith et al. (2005).

17.1.2 Micro-grids, Local Energy Communities, and Relative Research

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 (2020) and at Swedish level under § 22 (a) of the IKN Regulation 2007:215 (Riksdag 2020). 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 pro-sumers organize in energy communities, in which the excess production could be sold to other members (Parag and Sovacool 2016). The benefits are threefold as the pro-sumers 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.

In order to support new regulations, careful design and optimal modelling of P2P business models for PV penetration is necessary by analysing current state of affairs and proposing future ways of exchanging energy. Huijben and Verbong (2013) summarized three possible ownerships of PV systems, such as Customer-Owned (single ownership), Community Shares (multiple ownership) and Third Party ownership. Based on these possibilities, Lettner et al. (2018) further described three different system boundaries of a PV prosumer business concept (as illustrated in Fig. 17.1): 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

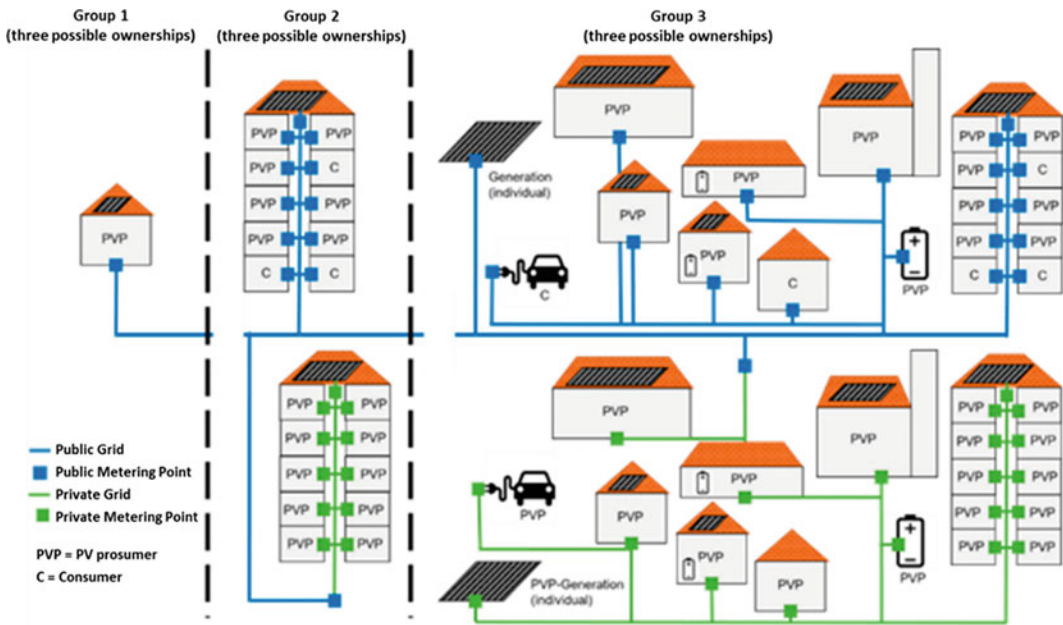
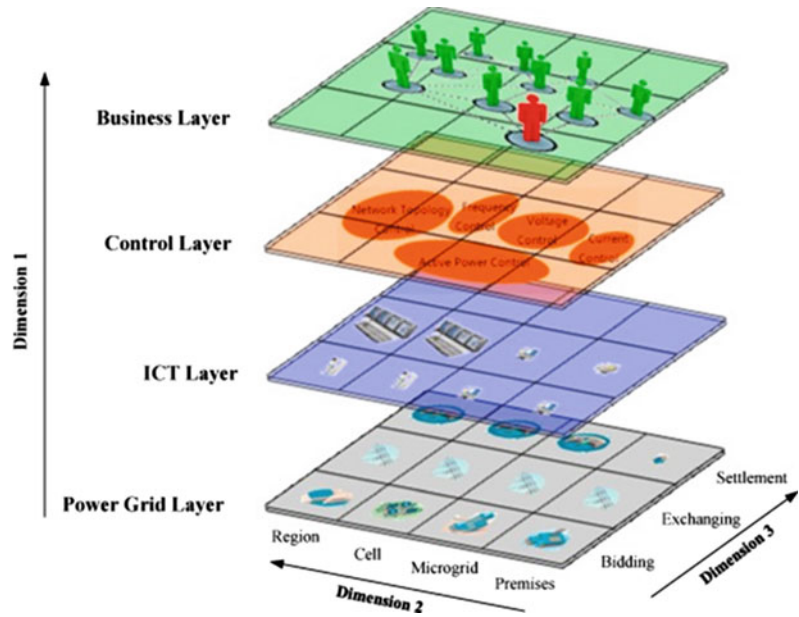


Fig. 17.1 Classification of integration concepts (Lettner et al. 2018)

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 micro grid). It is possible to have different ownerships in each category of these boundary conditions, resulting in a large number of 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 (Stauch and Vuichard 2019). 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 (Roberts et al. 2019). Zhang et al.

(2018) established a four-layer system architecture of P2P energy trading (as shown in Fig. 17.2, 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 micro-grid with 10 peers. A price mechanism for the aggregated PV electricity exchange among peer buildings was also developed using either Lagrangian relaxation-based decentralized algorithm (Xu et al. 2017) or mixed integer linear programming (Nguyen et al. 2018). Jing et al. (2020) 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. (2018) 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

Fig. 17.2 The four layered system architecture of P2P energy trading from Zhang et al. (2018)



batteries and optimized 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 (Rodrigues et al. 2020). These existing studies almost cover all the 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 (Tang et al. 2018), gas storage (Basnet and Zhong 2020), heat pump/hot water storage (Huang et al. 2019), advanced control (Thomas et al. 2019), energy cost optimization (Alam et al. 2019), bidding strategies for local free market (El-Baz et al. 2019), double auction market (Chen et al. 2019), local market designs (Sousa et al. 2019), integration of local electricity market into wholesale multi-market (Zepter et al. 2019), micro grid ICT architecture (Cornélusse et al. 2019) and grid operation (Almasalma et al. 2019) etc.

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 pro-sumers) 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 (Zhang et al. 2018), 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.

17.1.3 Novelty and Aim

A number of studies have focused on the technical or economic aspects of the micro-grids and shared RES, but the endeavor has been tackled in a segmented way analyzing a narrow sample of possibilities among the vast search space of the business models. The existing studies have not yet fully test the effectiveness and compare the characteristics of various P2P business models, in 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 the study in this chapter analyses only 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 chapter, although not conclusive by themselves, they are part of a well-defined search-space. This allows the outcomes to be interpreted from the perspective a larger systematic endeavor.

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

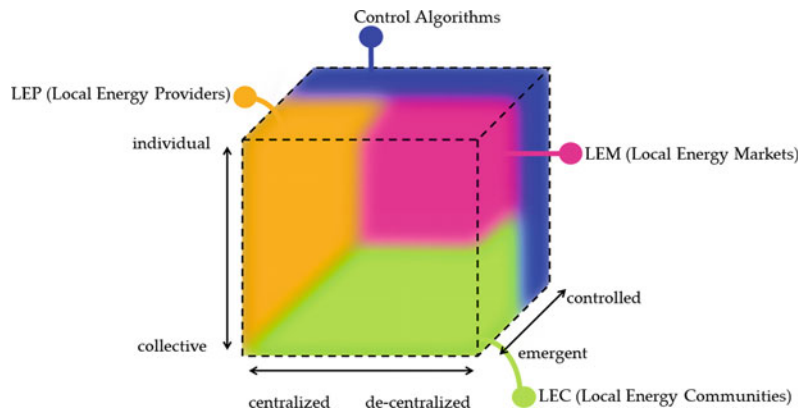
1. The particular result of the study: to the knowledge of the authors, no study have linked the price of the electricity offered within a shared RES to both the risk of economic loss and the potentials for earning

among the individual households within the shared micro-grid. Furthermore, the dominance of sheer annual cumulative consumption over self-sufficiency in determining the earning potential in a shared RES is an unknown phenomenon. It deserves to be further analyzed (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 Fig. 17.3). This facilitates a systematic inquiry and offers a way to organize the results presented in the study of this chapter and in the follow-ups.

This chapter reports the results of a study of the P2P business model for 48 individual building prosumers with PV installed in a Swedish community. The aim is to discover ‘latent opportunities’ that were previously unknown and optimize the market design and its variables for the best benefit. It will have significant influence that integrates energy needs, supply and market rules. This chapter is expected to provide knowledge for policymakers to design a fair, effective and economical P2P energy framework. The research results will be useful to optimize PED’s three functions (energy efficiency, energy production and flexibility) towards energy surplus and climate neutrality.

Fig. 17.3 District scale renewable energy systems behaviour map



17.2 Method

The definition of ownership structures from Huijben and Verbong (2013) 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 share-holder of an energy provider, or more providers, which form a market although not prosumers etc.). Thinking about the behaviour of the shared system, a space can be defined according to three dimensions (see Fig. 17.3):

- (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 centralized versus de-centralized 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 (Zhang et al. 2018), 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.

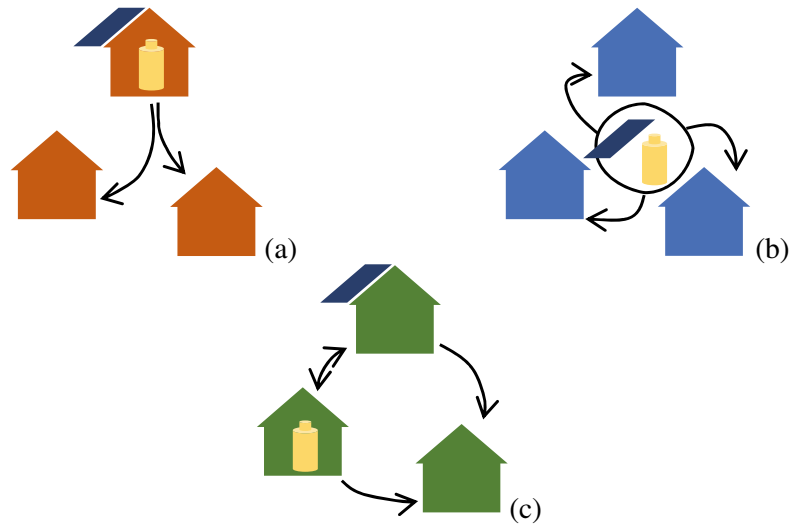
17.2.1 Agent Based Modelling

Given the number and nature of the emergent behaviours in the behaviour map (i.e. Fig. 17.3), an agent based model (ABM) simulation was developed to get an insight on 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. Example of producers are energy providers. 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 micro-grid 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 micro-grid 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 prioritize 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 prioritize 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

Fig. 17.4 Ownership structures organized in three main families: Local Energy Provider (LEP) (a), Local Energy Community (LEC) (b) and Local Energy Market (c)



explained in the following section (i.e. ownership structures and business models).

Figure 17.4 presents the possible ownership structures arranged in three main families, these are slightly different from those in Huijben and Verbong (2013) for the purpose of this study:

- (1) Local Energy Provider (LEP) (a in Fig. 17.4): 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) (b in Fig. 17.4): 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) (c in Fig. 17.4): It is the most complex and free-form of all the structures, it is characterized 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.

17.2.2 Ownership Structures and Business Models

In the case study examined (see following Sect. 17.2.4), a communal PV plant is shared among the different households in the building. This allows for all of the three basic ownership structures from Fig. 17.4 to be applied, because it is possible to create a LEM by having some household who own share of the large PV system. The ownership structure is intertwined with the business model and the rules of the market. In the following pages, the same communal PV plant is shared between the households in the local grid in three different market cases for LEC and LEP:

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 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 the Sect. 17.2.4) as the consumers retain the right to purchase electricity from the cheapest source.

After these three cases, 6 LEM scenarios are analysed. Due to the inherent complexity of this ownership structure, the characteristics of this simulation are explained in a dedicated paragraph (i.e. Sect. 17.2.3).

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 the arrangements, the consumer is programmed to buy electricity from the cheapest source. But 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, in 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 (17.1).

$$\begin{cases} E_{local} = \eta \cdot D_{local} \\ E_{house} = \eta \cdot D_{house} \\ D_{local} = \sum D_{house} \end{cases} \quad (17.1)$$

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 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.

The equations in (17.1) imply 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 (17.1) 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 (17.2):

$$P_{house} = P_{local} \cdot \eta + P_{parent} \cdot (1 - \eta) \quad (17.2)$$

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 (17.1).

Considering that η is the same for every household in the local grid as shown in (17.1), the Eq. (17.2) 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 function of any given household. This fact holds true also for the LEM case, in fact, in every time-step, the unique price in the micro-grid is equal to the average of the different prices of each available source. This average is weighted for the relative power of each source, thus, if a cheap source can satisfy a significant fraction of the demand, it will sensibly drive down the unique price. Of course, the ability of each single household to consume its own power, or at least to consume more power in cheap time-steps will affect the average price of electricity it pays (see Fig. 17.12).

To simplify, the agent based model can be described by a simple set of rules:

- (1) Every household is represented by one independent agent in the simulation.
- (2) Every agent has an energy balance in each HOY (Hour Of the Year). The energy balance is determined by its PV power (if it owns a PV system) minus its power demand in that particular HOY. If the balance is negative, the agent will be a net buyer in that HOY, otherwise it will be a seller. This rule implies that each agent can only sell electric power if it has already satisfied its own demand. Simply, each household can sell only excess PV production.
- (3) Each seller can set the price for the power he has to export.
- (4) If the electricity is offered by multiple sellers, the buying agent will buy preferentially by the cheapest source.
- (5) If the aggregated demand of the district exceeds the offer of the cheapest source, the demand of each household is satisfied proportionally by the cheapest source. If, for example, the cheapest source covers 30% of the aggregated demand in that HOY, each household is provided 30% of its power demand by the cheapest source (see equations in 17.1).
- (6) If the on-site renewable power exceeds the power demand in a certain HOY, the cheapest sources are consumed preferentially, while the more expensive ones risk to

be in excess of the demand and sell part (or all) their power to the grid. Those who sell to the grid cannot set the price but are simply valued the price paid by the grid (which is always way lower than that of the local sellers).

17.2.3 The LEM (Local Energy Market)

The LEM, being a more loose aggregation of stakeholders, is open to higher complexity and is thus studied in more detail, in this Chap. 6 scenarios have been hypothesized to study different behaviours within a LEM.

17.2.3.1 Scenario 1

All residents agree to purchase the PV system, every household purchases an equal share of the total system and has thus the right to 1/48 of the power at any time (I.e. ca. 1.36 kW each). The price for the sale within the micro-grid is agreed for the long term as the summer grid price/1.2 (thus a static 1 SEK/kWh at the year 0), therefore whoever buys electricity from another household saves ca. 17% on the electricity cost in summer and 45% in winter.

17.2.3.2 Scenario 2

All residents agree to purchase the PV system, likewise scenario 1. The price for the sale within the micro-grid is agreed for the long term as 99% of the grid price, therefore whoever buys electricity from another household has almost no savings compared to the grid. In this case it is assumed that using local energy is perceived as a value in itself by the participants in the grid.

17.2.3.3 Scenario 3

Only 50% of the residents agree to purchase the PV system, every PV equipped household purchases an equal share of the total system and has thus the right to 1/24 of the power at any time (I.e. ca. 2.73 kW each). The price for the sale within the micro-grid is agreed for the long term as the summer grid price/1.2, likewise in scenario 1.

Table 17.1 PV capacities per household and prices in the 6 different scenarios

Scenario	PV capacity (kW/household)	Electricity price (at year 0) (SEK/kWh)
(1)	1.36	1
(2)	1.36	1.19 (summer), 1.78 (winter)
(3)	2.73 or 0	1
(4)	2.73 or 0	1.19 (summer), 1.78 (winter)
(5)	1.36	1 or 1.19 (summer), 1.78 (winter)
(6)	1.36	1 or dynamic

17.2.3.4 Scenario 4

Only 50% of the residents agree to purchase the PV system, every PV equipped household purchases an equal share of the total system likewise in scenario 3. The price for the sale within the micro-grid is agreed for the long term as 99% of the grid price, likewise in scenario 2.

17.2.3.5 Scenario 5

All residents agree to purchase the PV system, likewise scenario 1. The price for the sale within the micro-grid is left to the choice of the single household, 50% of the households decide to charge a high price (i.e. 90% of the grid, like case 2 and case 4), the others charge the summer price /1.2.

17.2.3.6 Scenario 6

All residents agree to purchase the PV system, likewise scenario 1. The price for the sale within the micro-grid is left to the choice of the single household, 50% of the households decide to adopt a dynamic price system based on their energy balance in every hour of the year. With this strategy the energy is sold at LCOE whenever the balance is more than double the average balance in that hour of the day. The other 50%

charges the summer price /1.2 likewise scenario 1 and scenario 3 (Table 17.1).

17.2.4 Case Study Description

The agent based model is tested on a digital representation of a moderate size residential district (see Fig. 17.5) equipped with a shared PV system + DC micro-grid as described in Huang et al. (2019). 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 17.2. In total, there are 3 arrays on the roof and one on the southern façade (total 65.5 kWp).

The system capacity and the position of the arrays over the building resulted from an optimization process, presented in Huang et al. (2019), in order to maximize 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:



Fig. 17.5 Bird view of the small district in the case study (Huang et al. 2019)

Table 17.2 Characteristics of the shared PV system

Block	Facing	Tilt (Deg)	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

- 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 2 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 is 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 have been calculated from PVGIS (Šúri et al. 2005). The load profile of the 48 households could not be published for privacy concerns. Thus, the study is presented using data generated by the LPG (Load Profile Generator) software (Pflugradt and Muntwyler 2017). 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 (Pflugradt et al. 2013). 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 Fig. 17.6). 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 a need 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) has been 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 have been 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

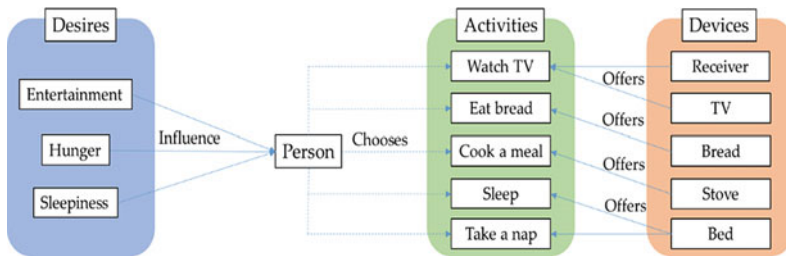


Fig. 17.6 Workflow diagram of the load electricity generation (Pflugradt and Muntwyler 2017)

(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.

17.3 Results

The results 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 its 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.

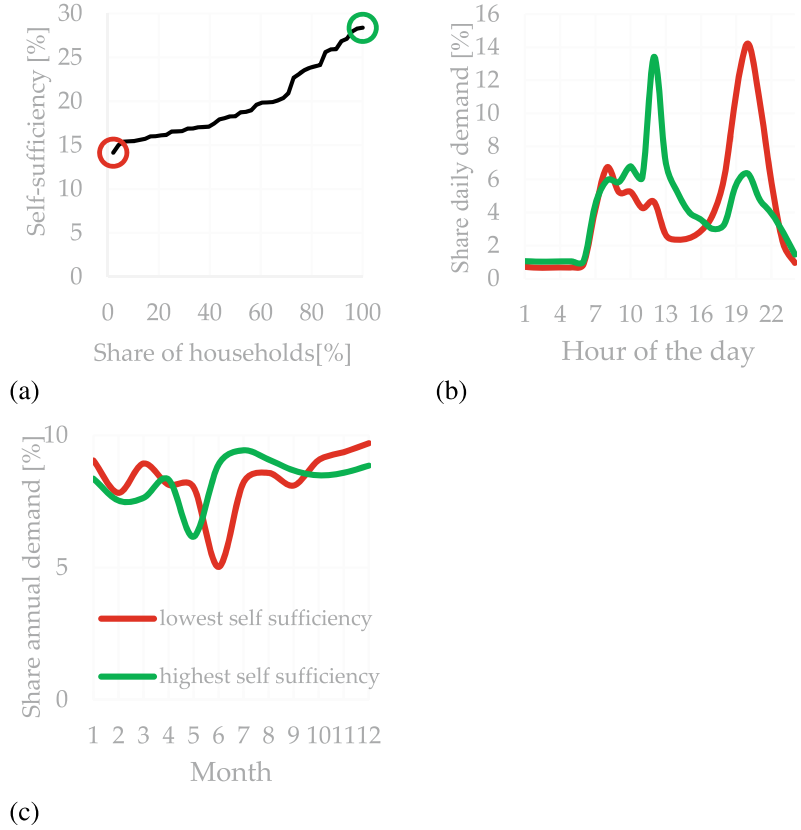
17.3.1 Self-sufficiency of the Households

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 (Luthander et al. 2015). 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. For a reference, according to IEA 2020b 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 Lovati et al. (2019) and (Huang et al. 2019) 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 Fig. 17.7a: 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 Fig. 17.7a). The P50 (i.e. 50 percentile) household has a relatively low self-sufficiency because there is a positive correlation between annual cumulative demand and self-sufficiency (see discussion about Fig. 17.9). In general, the variability in self-sufficiency between the households in the micro-grid 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 out the most from the available PV energy.

Figure 17.7b and c show the share of the annual demand in different hours of the day or month of the year respectively: this is to say 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 Fig. 17.7b). It indicates that its inhabitants use to 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 (Fig. 17.7c), the difference is less marked

Fig. 17.7 Self-sufficiency of the apartments in the local grid. **a** is the distribution of self-sufficiencies across the 48 households, **b** shows the hourly average of the extreme households, **c** shows the monthly average consumption of the extreme households



compared to the daily average: both the 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 Fig. 17.7c. 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 at the presence of some household's components at home.

The examples shown in Fig. 17.7 highlight the two apartments that are extreme in terms of self-sufficiency. To infer more generalized information on the time of high consumption that favors high self-sufficiency (see Fig. 17.8) the following formula was used:

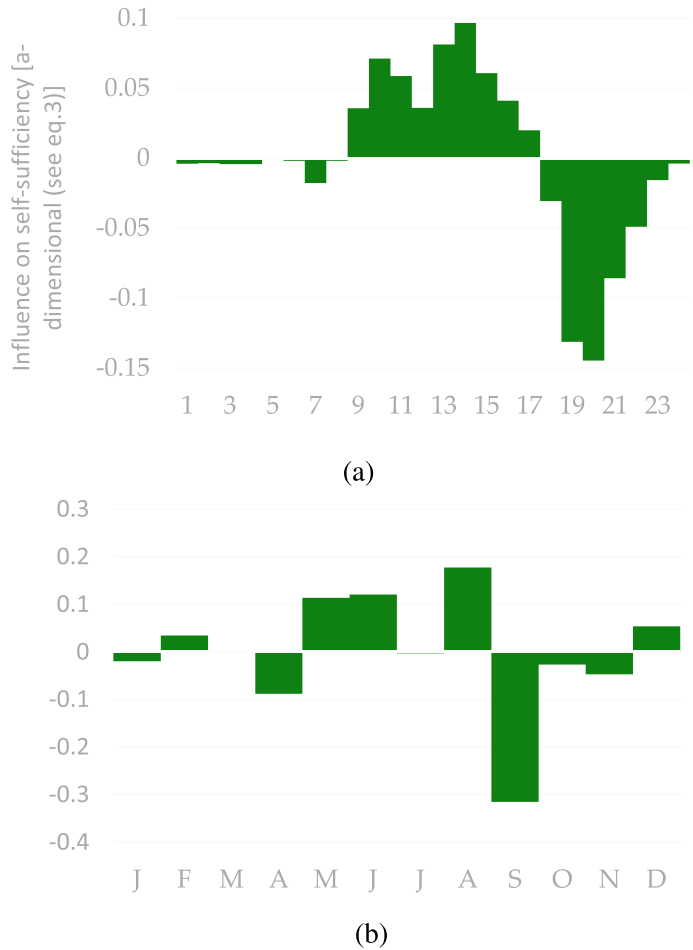
$$ISelfS_{ts} = \sum_{HH=1}^{48} \begin{cases} TP_{ts,HH} - TP_{ts,Tot} & \forall SelfS_{HH} \geq SelfS_{tot} \\ 0 & \forall SelfS_{HH} \leq SelfS_{tot} \end{cases} \quad (17.3)$$

where

$ISelfS_{ts}$ 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. $TP_{ts,HH}$ and $TP_{ts,tot}$ are the typical power demand [W] of said time step(ts) for the nth household (HH) or 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, Fig. 17.8a shows that a lower average demand in the evening and early morning hours is

Fig. 17.8 Influence on self-sufficiency of high demand in **a** each hour of an average day; and **b** month of the year. The value is a-dimensional but it express the positive (or negative) influence of a high electric demand at a given time-step compared to all the others (see Eq. 17.3)



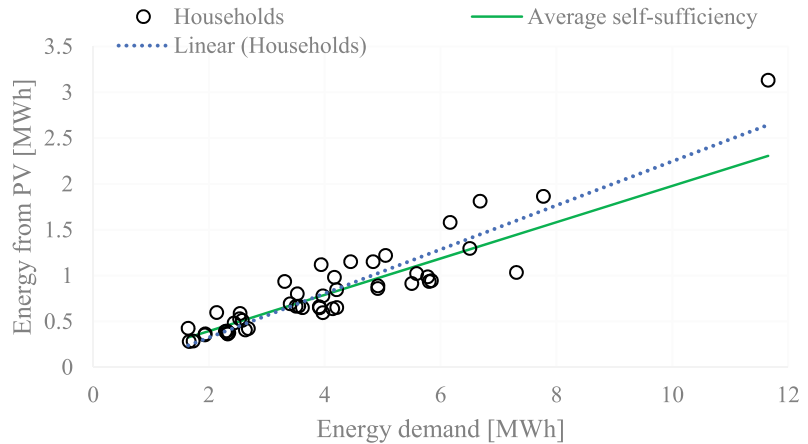
associated with high self-sufficiency. On the contrary, the central hours of the day are generally above average in highly self-sufficient households. It is interesting to notice how the electric demand at 12:00 is in general less beneficial for self-sufficiency than the hours around: this is somewhat counter intuitive, 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 into holiday later in any given year. Given the sharp drop in irradiation of the month of September

compared to July and August, it seems reasonable that going to holiday in September increases the self-sufficiency over the year.

17.3.2 Exploitation of the Common Renewable Resources: Sheer Cumulative Consumption Versus Self-sufficiency

Figure 17.9 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

Fig. 17.9 Annual cumulative energy demand and annual cumulative energy used from the PV system for every household in the local grid



with good confidence from the annual cumulative demand alone (i.e. regardless of the self-sufficiency).

This aspect, although counter-intuitive, 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 5 times the lowest one (excluding the highest value as an outlier, otherwise is more than 7 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 Fig. 17.9). 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 has an individual household 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 Fig. 17.8, 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 tend 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.

17.3.3 LEC Gratis

In this arrangement, the households in the district are shareholders of the system. So 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, a price of the electricity for non-owners should be established (see section LEP n%).

Figure 17.10 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 “Ownership structures and business models” that at any given time the price of the electricity is unique within the micro-grid and depends from the relationship between production of PV and demand (see Eqs. 17.1 and 17.2). The bars in Fig. 17.10 are the average of all the 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, because the Eq. (17.2) with $P_{local} = 0$, 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.

Even if the price of the electricity is the same within the micro grid 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 that a higher self-sufficiency will lower the average price. However, in terms of gross economic

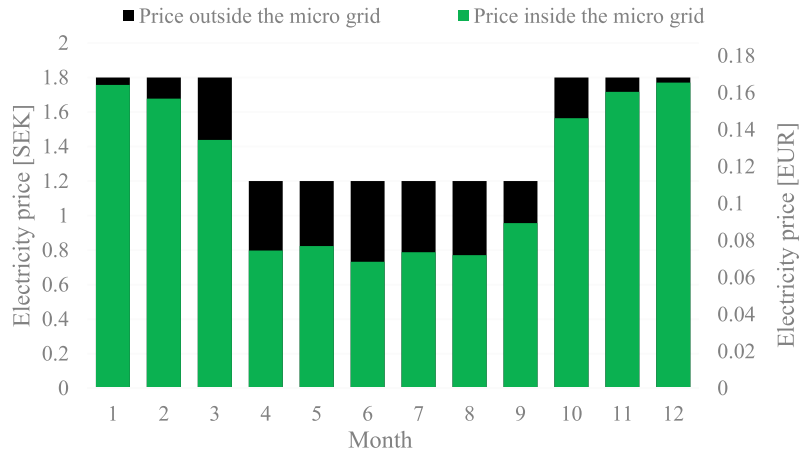
benefit (i.e. the sum that can be saved), it is not the average price that matter, but the cumulative energy received for free. In this sense, the conclusion from Fig. 17.9 is troublesome as the earnings are not due to the ability to obtain a higher self-sufficiency, but simply to the sheer cumulative consumption. In Fig. 17.11, the households in the micro-grid are divided in 3 groups of 16 elements each according to their annual cumulative consumption. As in Fig. 17.9, 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. From Fig. 17.11a 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 case of the initial investment of 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.

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.

17.3.4 Lec Lcoe

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 17.11a and b) follow a linear transformation from the extreme inequality (as in Fig. 17.10a),

Fig. 17.10 Monthly difference in price between the energy offered by the parent grid and the average paid by the shareholders in a LEC gratis arrangement



to a situation of complete equality of earnings (if a LEC grid-price is hypothesized), 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.

17.3.5 LEP N%

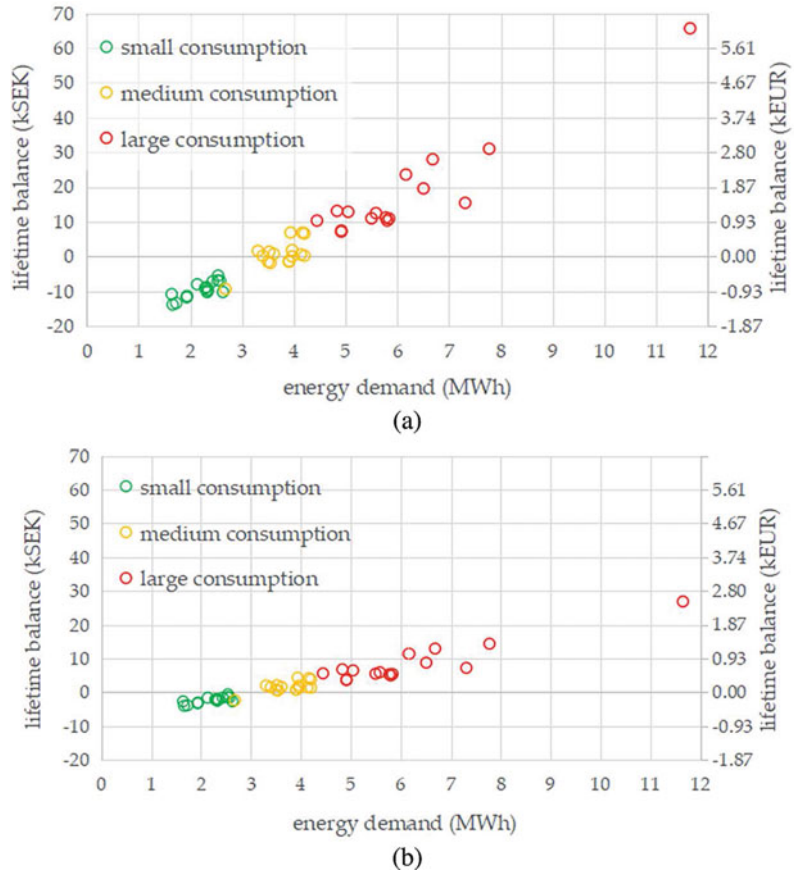
In this arrangement, the PV system is owned by a single provider who has the right to set the price. Obviously, since the parent grid has the ability to supply 100% of the demand of the district, the owner cannot set the price higher than the electric grid lest being completely out-bid (e.g. no household 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 17.3 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.

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 due to the fact that 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 Huang et al. (2019). 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 Fig. 17.11b). 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

Fig. 17.11 Cumulative balance over the lifetime of the system against the lifetime of the annual energy demand. The households have been divided in 3 groups, each of 16 specimens, according to their cumulative consumption. **a** LEC Gratis, **b** LEC LCOE



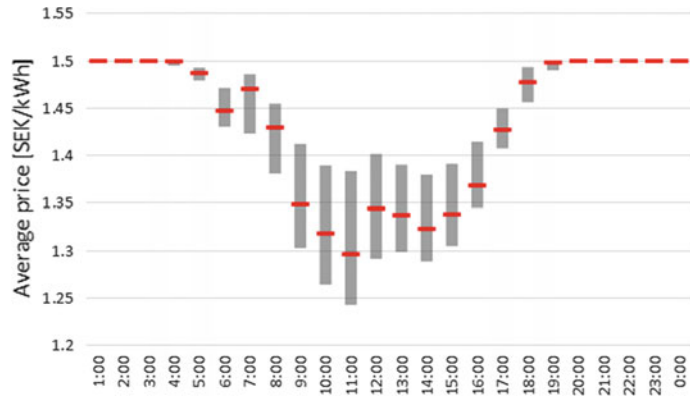
alternative material. Furthermore, this price tag is extremely interesting as price of sale from LEC. It in fact presents the advantage of expected lifetime economic balance in positive ground for each household.

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 nor upfront investment and could receive information about their own self-sufficiency by the provider, e.g. with a monthly email.

17.3.6 LEM

Figure 17.12 describes the average hourly price for scenario 1 during the different hours of the day within the district. The grey bands represent the variability between different households of the district. If a bar is longer, it means that some households have an average price that is significantly lower than others in that hour of the day. The red ticks represent the average price in that hour for the whole district. It is immediately visible that between 7 P.M. and 4 A.M. the price is almost stable at one point five SEK. The price is stable because there is no electric storage installed in the micro grid and therefore, when a photovoltaic system is not producing, the price is

Fig. 17.12 Average price for each hour of the day and its variability within the district (LEM, Scenario 1)



that of the power provided by the electric grid. Considering that the night-time consumption of the district remains stable throughout the year, And that the the electricity is sold at 1.8 SEK/kWh in winter and 1.2 SEK/kWh in summer, the night price paid by the whole district equals almost exactly the average of the two (I.e. 1.5 SEK/kWh). During daytime the price is lower, there are two reasons for this phenomenon. The first reason is that each household owns a share of the local PV system, and therefore all the electricity produced by their own share already belongs to them, and is thus free for themselves. The second reason is that they can purchase electricity from their peers, which price is consistently lower than that of the grid. For these reasons, those households that are able to use larger share of their own electricity, or at least of the electricity from their peers, can enjoy a lower price for the electricity. It is visible, how indeed expected, that the price of electricity is generally lower during the central hours of the day. Furthermore, it can be observed that times of the day of comparatively higher price, correspond with moments of high electric demand. For example, it can be seen how the price is comparatively higher at seven and eight am (when people prepare and consume breakfast) and at noon (when many prepare and consume lunch). This is due to the fact that, despite a large photovoltaic production in that hour, the outlier

high demand forces the whole district to supply part of its demand from the electric grid.

Figure 17.13 shows the relationship between savings and revenues for each single households within the micro grid. All the sixth scenarios described previously are shown in the chart. In general, the savings are obtained either by using the electricity produced by one's own system, therefore saving 100% of the price from the grid, or else by using the electricity from a peer household at a discounted price. On the other end, the revenues are obtained either by selling electricity to the grid, or else by selling electricity to another household, the latter providing a much higher price. In each of the charts, every household is displayed as a circle, its position on the x axis represents its annual revenues, while its position on the y axis represents its annual savings. The color of the circle line represents its belonging to a different category, according to the number of people living in the household. In general, these charts should be studied in their relative difference between each other, rather than in their absolute values. In fact, the absolute value of revenues and savings are not interesting when the cost of initial investment and those for the maintenance of the system are not taken into account. To see the lifetime techno-economic performance of the system the internal rates of return should be investigated. Observing the colour in all the cases it is visible that the smaller

Table 17.3 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	-8'790	-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

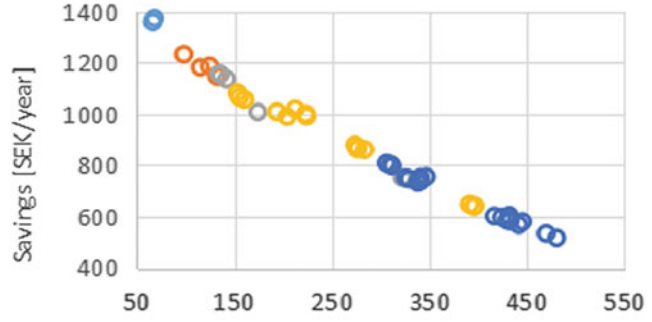
households, i.e. those which have a smaller electric demand tend to show lower savings and higher revenues. This phenomenon is quite unsurprising because in the example considered every household purchases an equal capacity to all the others. Therefore, the small households will have a PV capacity that is larger relative to their demand, and will, thus, export and sell a larger fraction of the electricity that they produce.

There is a noticeable difference between the scenario 1 and the scenario 2. In the scenario 1 every household agreed to sell their electricity at a significantly lower price compared to what they agree in the scenario 2 (see Table 17.1). Because of these, the scenario 1 seems to be particularly advantageous for the largest consumers. This is due to the fact that the largest consumers have high savings but low revenues, and therefore, the sale of electricity at a lower price from others leads to higher saving for them, while it does not impact their revenues significantly. On the contrary, the smallest consumers, that have in general lower savings and higher revenues, will benefit from higher price of the electricity. In this case, they will be able to increase greatly their revenues without changing too much their savings. In fact, being smaller, most of their savings comes from their own PV system, which is already over-dimensioned compared to their size. Going back to the largest consumers, a large fraction of their savings implies purchasing electricity from the smaller peers. Another noticeable aspect is that in scenario 2, all the points are almost linearly correlated. This is due to the high price of the electricity sold, which is almost the same of the cost of electricity from the

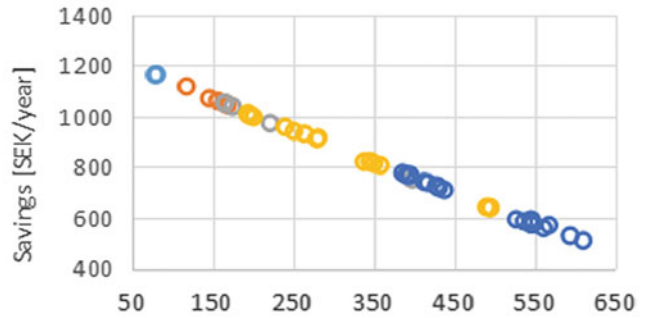
grid. The smaller remaining differences can be explained by the correlation between the private electric demand and the demand of the whole district. If an household over-produce electricity when the whole district is in over-production, its performances will be slightly lower because it will often sell to the grid. In the opposite case, when an household overproduces at times when there is need from other households, then its performance will be slightly higher.

Scenario 3 and 4 reflect scenario 1 and 2 in terms of price, but they have the peculiar aspect that only half of the households choose to purchase a PV system. This state of affair would be very important for any practical application of the micro-grid. This is because, in practice, it is really difficult to convince 100% of the tenants in a multi-family dwelling to participate, and especially to invest money, in a PV system. In a realistic setting it is expected that part of the population is unwilling to invest in the system, nevertheless, in the simulation is assumed that they decided to participate in the micro-grid as simple consumers (i.e. those who do not own any part of the system). The assumption is pretty safe because being a simple consumer only requires to always purchase the electricity from the cheapest source. In this way, to participate as a simple consumer does not have any initial cost, but it might have a benefit during the lifetime of the system. If scenario 1 is compared to scenario 3, it is visible that the points in the latter overwhelmingly outperform those in the former both in terms of revenues and in terms of savings. It is tolerably intuitive that, if only half of the households own a PV system, their revenues will

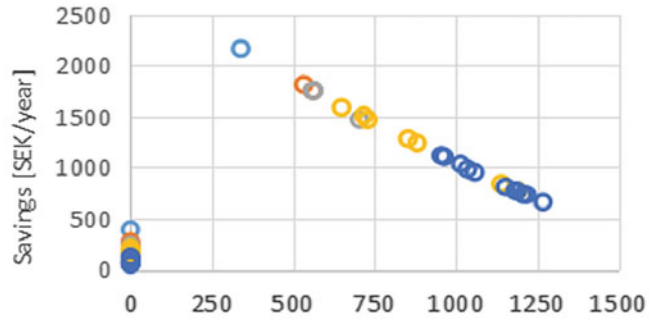
Fig. 17.13 Savings versus revenues for each household in the microgrid. Both axes are in [SEK/year]



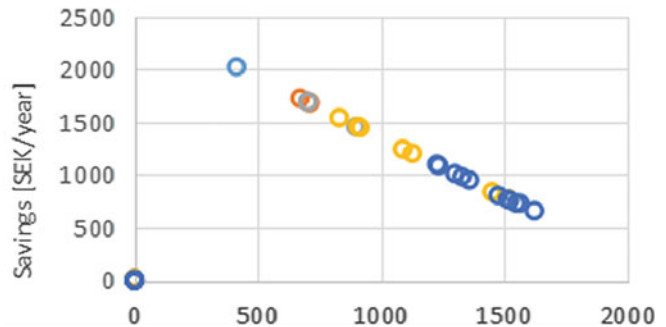
(1)



(2)

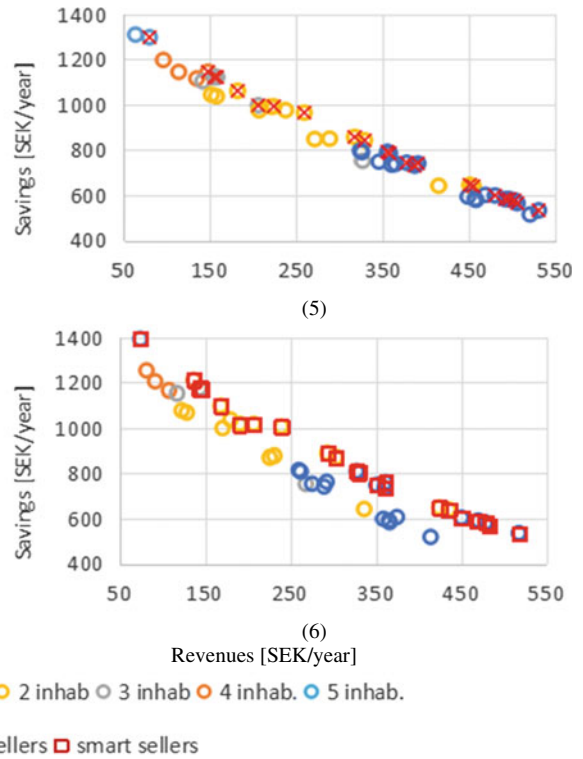


(3)



(4)

Fig. 17.13 (continued)



increase. In fact, all the households who do not own PV can only buy the electricity from those who own it, and therefore, the whole local market moves in the direction of a “seller’s market”. Also the increase in savings is readily explained, In fact, since the optimal capacity is unchanged in every scenario, every PV owner has at his disposal a larger capacity. This fact implies that there is more available electricity for self-consumption in every HOY, even at times of a relatively high private electric demand. This spare over-capacity favours an increase in self-sufficiency. Looking at the bottom left corner of the chart for scenario 3, it can be seen how there is a benefit in terms of savings also for those who do not own a PV system. Of course, these savings are minor compared to those of the other households, and this is due to two specific reasons. The first one is that, by lacking a PV system of their own, these households do not have their own electricity for free, and therefore can only purchase electricity from their peers. The second reason is that every household, before to

sell electricity, satisfies his own demand, and therefore those in the micro-grid who do not own a PV system can only benefit from the left-over electricity from the others. In other words the household without PV can only purchase electricity when they happen to be in need of power at times when others are in over-production. Scenario 4, like the scenario 2, presents a linear correlation between the revenues and the savings of each household. Like scenario 2 over scenario 1, also scenario 4 presents a relatively higher revenues and lower savings compared to scenario 3, thus favouring the smallest consumers. Furthermore, like scenario 3, it presents a sharp contrast between the PV owners and the other households. It should be noted, though, that this time there is absolutely no benefit in participating in the micro-grid, or at least the benefits are so tiny that cannot be seen by the naked eye. There is nevertheless a benefit for those household, it is the possibility to increase the share of renewable on-site electricity in their energy consumption. It can be expected that, given the absence of initial

investment, most consumer would be willing to increase their renewable energy share. It is presented to them the possibility to save the planet with a cost-less, thus effortless, action.

In the first four scenarios the price for the sale of PV power And the number of PV owners has been changed. Nevertheless, in all these cases, every PV owner agreed to maintain the same price as everybody else. In scenario 5 the hypothesis is made that a half of the PV owners prefer to sell at the lower price (I.e. the price of the whole group of PV owners in scenario 2 and 4). Meanwhile the other half of the owners prefers to sell at the same price of scenario 1 and 3. Observing the revenues and the savings in this arrangement, it can be noted that, in general, the sellers who decide to sell for a lower price (I.e. shown as 'cheap sellers'), enjoy a higher revenues compared to the others. First of all, let's consider that savings are not affected by the price for the sale of one's own electricity, but rather by the price for available energy from the other households. For every saving level in the chart, the lowest selling households, which are marked as 'cheap sellers', appear to be on the right side compared to the others, this means that they have managed to obtain higher revenues. There are two factors at play when measuring the revenues in this type of market (I.e. where there are two different prices groups). The first factor is the sheer revenues per KWh sold, this it acts by lowering the revenues for the so called 'cheap sellers'. The second factor regards the ability to effectively sell your electricity within the micro grid at all (i.e. the capacity of not be in over supply, Thus forced to sell most of your power to the grid). If a different price was chosen, the result might have been different, but in this case the increased revenues deriving from an higher price scheme are not enough to offset the increased instances in which the electricity cannot be sold due to high price and low demand. Also in scenario 6, the last one, the group of households was divided into 2 sub groups. As in the previous scenario, some households where

selling their electricity at a lower price compared to others. This time, though, the expensive sellers were given the ability to change the price according to a behaviour of their own. The mechanism used to change the price was set according to the simple principle explained in the description of scenario 6. In practice, these households, identified in the chart as 'smart sellers', will sell their power at the LCOE of the system, which is lower than the static price of the cheap sellers, whenever they have an outlier high energy balance. In other words, when a smart seller has an outlier, low power consumption or an outlier high power production from PV, it will sell its electric power at the lowest possible price. This strategy is extremely simple and is prone to numerous fallacies. In fact, if for example a particular household is on holiday during an unpopular period (I.e. when nobody else is on holiday), its power demand would be unusually low, thus resulting in an outlier high balance. This could cause it to sell at LCOE in a time in which the electricity is indeed in high demand throughout the district. In this example, the household would be selling at the lowest possible price in a time in which the maximum price would still manage to sell to the peers. Conversely, if an household will experience an outlier high demand for its own reasons, it might find itself selling its available power dearly, while there might be plenty of energy available for everyone. In this case it will be forced to sell most its power to the electric grid. Despite the simplicity of this strategy and its obvious flaws, it is visible from the chart (Fig. 17.13 (6)) that such a simple behaviour is good enough for outsmarting the cheap sellers in the competition for the sale of electric power. Given any savings level, the smart sellers undeniably manage to obtain higher revenues. This is a very important result because it shows that it is possible to create an effective strategy without knowing the consumption of the other agents in the micro grid, thus, avoiding privacy issues.

17.4 Discussion and Outlook

17.4.1 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 Eqs. 17.1 and 17.2). 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 Fig. 17.7a). 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. From Fig. 17.7b 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 8 P.M. 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.

17.4.2 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 Fig. 17.9). This phenomenon, albeit counter-

intuitive, is due to the fact that the variability of cumulative demand far outweighs the variability in self-sufficiency (the largest being 5 or even 7 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 Fig. 17.13). The balance in a LEC gratis arrangement (Fig. 17.11a) 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 in 3 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 be also 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 anyway 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 outcome 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.

17.4.3 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 to 0.15 SEK/kWh or 3 to 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 Fig. 17.11b. Another interesting selling price is the one obtained with $n = 9.43\%$ because this is the price at which no profit nor loss is made from the LEP. This price tag, albeit unattractive as an investment for a third-party PV owner, presents an interesting mean 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 the household 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 nor risk. Furthermore, the possibility for the households to buy voluntarily sized shares of the LEP could kick start a set of tantalizing business opportunities.

17.5 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 17.3).

17.5.1 Key Findings

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

- 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. Yet, some households achieved a self-sufficiency of almost 30% using the common PV system while others stopped short of 15%. also in the LEM case, where a more accurate study of the energy demand were made, a similar result was obtained.

- 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 the Sect. 17.2.2, 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.

17.5.2 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 favor 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 + long term linear trends for sold and bought electricity) into a spot-price + distribution costs. However, while the

change reflects reality better, the long term (multi-annual) modelling of the spot-price would be a daunting task and affected by huge uncertainty. Because of this reason, it might pay off to just maintain a simplified model for the prices (i.e. 2 seasonal prices for purchase and sale + 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. And, 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 either a unique actor (be it a community or a provider) or by two groups of actors (such as in scenario 5 and 6 of the LEM). 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, beyond the simple behaviour of the smart sellers, and let them adjust the price reacting to the environment to maximize 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 micro-grid, it is possible to find correlation with socio-economic 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 as well affected by socio-economic 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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