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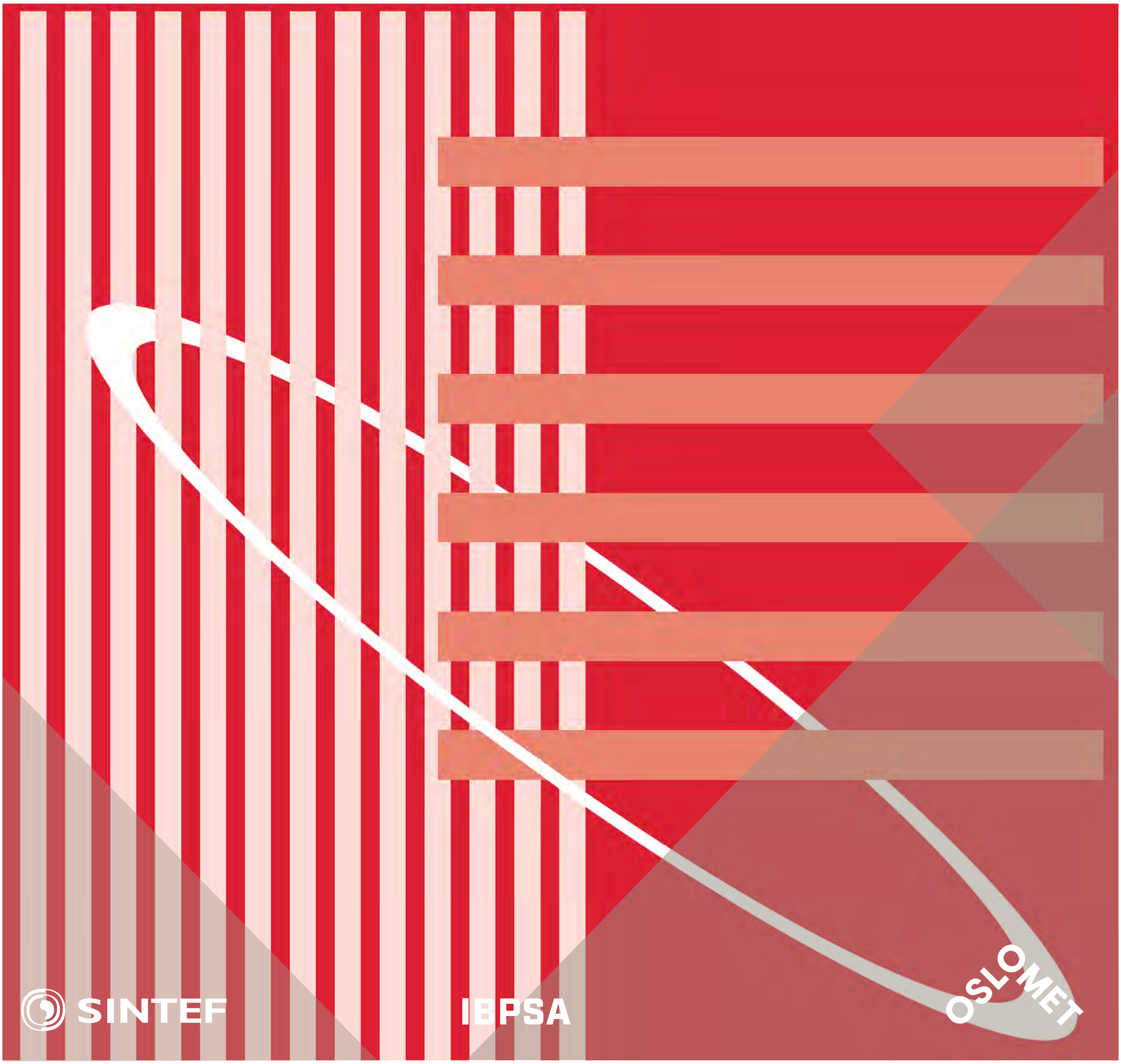

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Insight on a local energy community: Agent based model of a peer to peer (P2P) interaction for a group of prosumers

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Abstract

Energy communities are becoming a promising opportunity for distributed energy systems in positive energy districts (PED), in which the electric energy is bought and sold in a neighborhood through a shared local infrastructure. The paper considers the complexity of the set-up using of ABM (Agent Based Modelling) as a mean to investigate how such communities work. The results of an ABM simulation regarding techno-economic matters in a small energy community (48 households) are reported and discussed. Different ownership structures and price schemes are tested and evaluated. The research result thus tend to discover 'latent opportunities' that were previously unknown and provide guidance to optimize the market design and its variables for the best performance, towards energy surplus, efficiency and climate neutrality in PEDs.

Introduction

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 by the IEA in annex 83. Solar photovoltaic (PV) is becoming one of most significant renewable sources in PEDs. The distributed systems are dominating the Swedish PV markets. The installed capacity of PV systems in Sweden is expected to continuously soar in the future, mainly contributed by homeowners and private or public companies at relatively small or medium scales (Swedish Energy Agency, 2016) according to its particular market setup and subsidy (e.g. SOLROT deduction, tax reduction, etc).

However, relying on subsidy is not sustainable for PV deployment. 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 net-metering mechanism), which are not applicable anymore for small PV systems (Huijben & Verbong, 2013). The existing business models cannot map the full potentials of both energy supply and demand, as well as energy sharing. So if there is no subsidy in the future, the prosumers (i.e. small PV owners) can only sell their excess production at market price back to grid, which is not only less profitable to PV owners, but also reduces reliability and stability of grid.

Fortunately, the regulation is changing positively in Sweden, which starts to allow the local sharing of PV electricity in a positive energy community under § 22 (a) of the IKN Regulation 2007:215 (Sveriges Riksdag, 2007). This can be an opportunity for a new business model development within energy sector, e.g. Peer-to-Peer (P2P) trading. In such business model, consumers and prosumers form up energy communities, in which the excess production could be sold to other members (Parag & Sovacool, 2016). 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 grid could be more stable and reliable. This can be a potential solution to promoting PV in a sustainable way, while reducing the dependency 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 scenarios and proposing future ways of exchanging energy. (Huijben & 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 (Schwabeneder et al.) further described three different system boundaries of a PV prosumer business concept: “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 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. So learning and mapping (i.e. testing) a wide array of these possible designs and combinations is necessary, especially for different energy communities within diverse contexts.

This paper thus aims to propose and simulates a series of P2P business models for 48 individual building prosumers with PV in a ‘virtual’ Swedish community. It considers the electricity/financial flows, ownerships, and trading rules in a local electricity market, using simulated load and generation profiles. Three different local electricity markets (single, multi PV ownerships and free market) are designed and studied using agent-based modelling, with different energy demands, cost-benefit schemes and financial hypotheses for performance evaluation.

Methodology

Agent-Based Model (ABM)

Because of the complexity of the interactions between prosumers in a micro-grid in the introduction, an 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 prosumers), but producers are not excluded. Example of producers are energy providers, i.e. companies or investor that interact with the local grid without necessarily being served by it, or the parent grid, i.e. the larger grid on 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 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 example 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, 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 explained in the following section (i.e. ownership structures and business models).

Figure 1 presents the possible ownership structures arranged in three main families, these are slightly different from those from (Huijben & Verbong, 2013) for the purpose of this study:

- Local Energy Provider (LEP) (a in Figure 1): 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 prosumers .
- Local Energy Community (LEC) (b in Figure 1): 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 share of the initial investment.
- Local Energy Market (LEM) (c in Figure 1): 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.

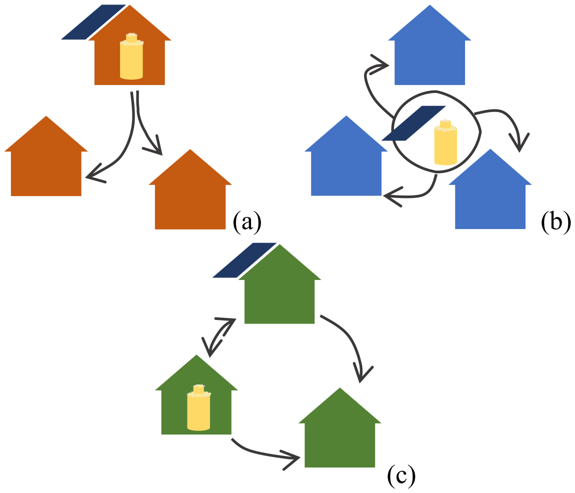

Figure 1: possible ownership structures organized in three main families: Local Energy Provider (LEP)(a), Local Energy Community (LEC)(b) and Local Energy Market (c).

Ownership structures and business models

In the case study examined (see case study section) a communal PV plant is shared among the different households in the building, this allow for two of the three basic ownership structures from Figure 1 (i.e. LEP and LEC). 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:

- **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 & Maintenance (O&M) costs of the plant according to equal shares.
- **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).
- **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 section "The case study") 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 exactly half-way.

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, and that 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 demand as shown in the system of relations in (1).

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

In (1):

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

The equations in (1) implies that having a larger consumption when the local electricity production is scarce guarantees access to a larger amount of local energy, albeit 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 (2):

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

Where:

- $\mathbf{P_{house}}$, $\mathbf{P_{local}}$ and $\mathbf{P_{parent}}$ 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.
- $\boldsymbol{\eta}$ is the self-sufficiency coefficient as defined for (1).

Considering that η is the same for every household in the local grid as shown in (1), (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 that the price for the electricity is solely function of the Hour Of the Year (HOY) and not of any given household.

The case study

Figure 2: bird's eye picture of the small district in the case study. The picture is taken from (Huang et al. 2019).

The agent based model is tested on a digital representation of a moderate size residential district (see Figure 2) equipped with a shared PV system + DC micro-grid as described in (Huang et al., 2019). The group of three buildings on 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 3 arrays on the roof and one on the southern façade (totalling 65.5 kWp).

Table 1: 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

The system capacity and the position of the arrays over the building resulted from an optimization process, presented in (Huang et al., 2019), 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 ca. 0.83 SEK/kWh (0.077 €/ kWh) under the following assumptions:

- initial price of the turn-key system without taxation: 10000 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 (Huld 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, 2016). 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 households 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 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.

Results and discussion

The results section begins with a discussion about the self-sufficiency of the different households in the local network, 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.

Self-sufficiency of the households

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 PVPS, 2020), 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 P_{50} household has a self-sufficiency of 18.5% as shown in Figure 2 (a): this value is below the value of the aggregated district because the slope of the increase is higher to the right of P50 (see Figure 2 (a)). The P_{50} household has a relatively low self-sufficiency also because there is a positive correlation between annual cumulative demand and self-sufficiency (see discussion about Figure 3). 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.

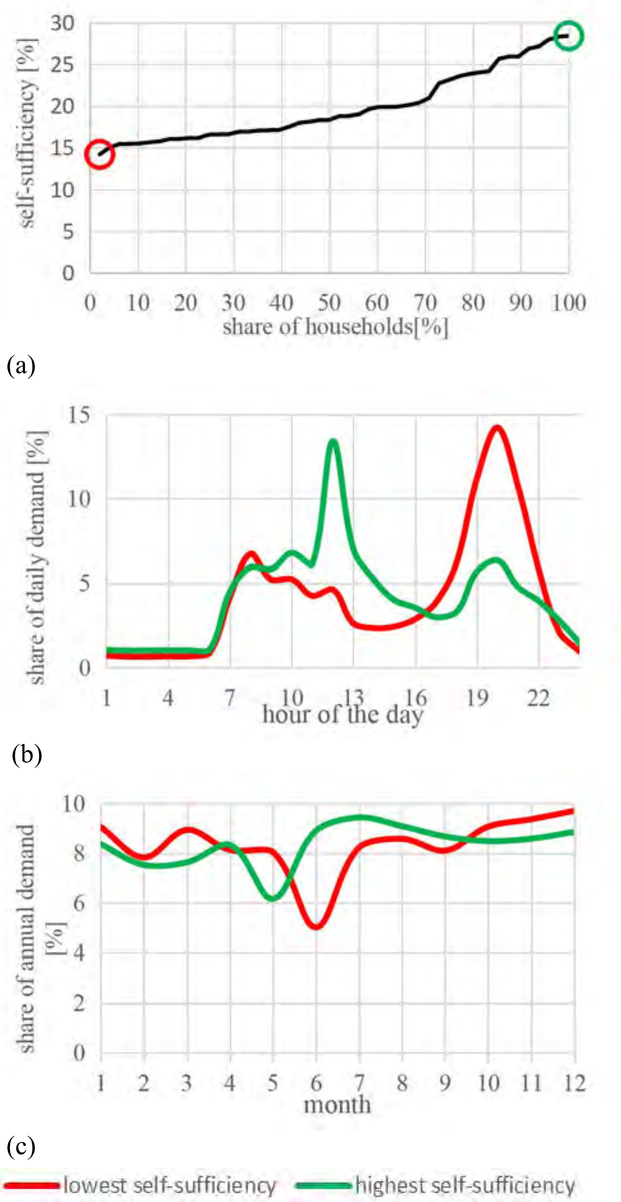

Figure 3: self-sufficiency of the apartments in the local grid. (a) is the distribution of self-sufficiencies across the 48 households,(b) shows the hourly average of the extreme households,(c) shows the monthly average consumption of the extreme households.

Figure 2 (b) and (c) shows the share of the annual demand in different hours of the day or month of the year respectively: which 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 Figure 2 (b)), 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 (Figure 2 (c)), the difference is less marked 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 (Figure 2 (c)), this might be advantageous as it allow 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.

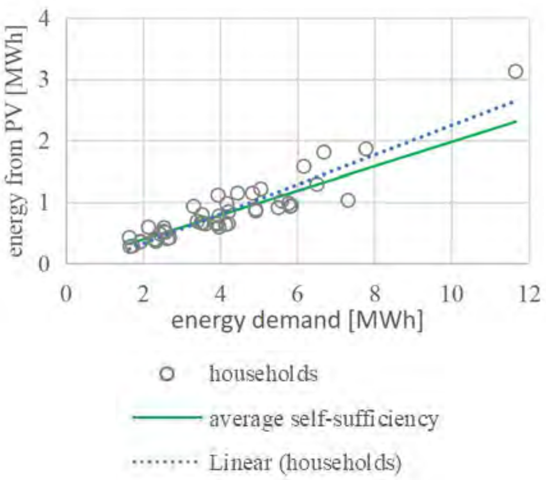

Figure 4: annual cumulative energy demand and annual cumulative energy used from the PV system for every household in the local grid.

Figure 3 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). 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 Figure 3). Furthermore, as self-sufficiency is a share of the demand, 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 Figure 3 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 highest annual cumulative consumption have also, on average, a highest self-sufficiency. A correlation analysis between annual cumulative consumption and self-sufficiency found a positive, albeit weak, correlation ($R \approx 0.2$). Although weak, 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 components who stay at home during daytime, or to electric consumption of people who spend daytime at home being larger overall.

LEC gratis

In this arrangement the households in the district are shareholders of the system and thus, when available, can use the electricity produced by the system for free. In this study the shares of the PV system are equal, each household will therefore have to pay 13646 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 example, 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 5 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, these 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 equation 1 and 2). The bars in Figure 5 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 of the Equation 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.

Figure 5: 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 micro grid at any given point in time , the average price paid by each household varies according to the time patterns of consumption. An household which consumed a large share of its annual consumption at times when the electricity was free (or at least cheaper) will enjoy a lower average price. 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 Figure 4 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 6 The households in the micro-grid are divided in 3 groups of 16 elements each according to their annual cumulative consumption. As in Figure 4 the correlation of the KPI 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 Figure 6 it is visible how being in the upper third of the cumulative consumption charts guarantees substantial earnings (IRR from 1.9% to 6%) given the initial investment of about 13646 SEK (1275 €/household). Conversely, the low-consumption households are doomed to economic losses, which means they are unable to recover the investment itself.

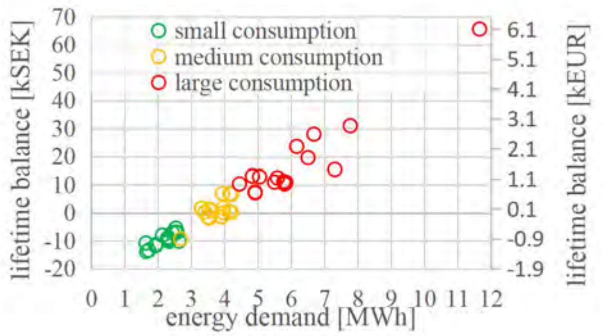

Figure 6: cumulative balance over the lifetime of the system against the annual energy demand (energy given free to the shareholders). The households have been divided in 3 groups, each of 16 specimens, according to their cumulative consumption.

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.

LEC LCOE

If instead of being given for free the energy is sold at production cost (LCOE), 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 6 and Figure 7) follow a linear transformation from the extreme inequality (as in Figure 6), to a situation of complete equality of earnings (if a LEC grid-price is hypnotized) where no benefit is obtained by the use of in-situ electricity. In the hypothesis that 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.

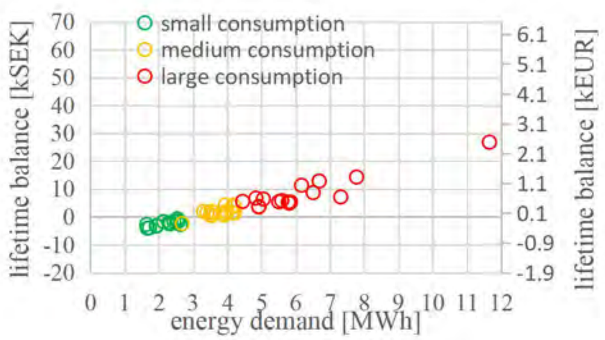

Figure 7: cumulative balance over the lifetime of the system against the annual energy demand (energy given at production cost to the shareholders). The households have been divided in 3 groups, each of 16 specimens, according to their cumulative consumption.

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 outbidded (i.e. 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.

Table 2 shows how the annual revenues, the balance over the lifetime and the real IRR (Internal Rate of Return) 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	-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

Notice how with n = 0 % (i.e. the electricity sold at production cost of 0.83 SEK/kWh) the balance, thus the IRR result 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 Figure 7). 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 forecasting the 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, for example with a monthly email.

Conclusion

In the study, a newly developed Agent Based Model was tested on a shared PV system serving a small district comprising 48 apartments. 2 different ownership structures were tried: LEC (Local Energy Community) and LEP (Local Energy Provider). The LEC arrangement was tried 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). 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 3 a). 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 Figure 3 (b) 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. 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 4). 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) 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 in fact transposed in the relation between energy consumption and lifetime balance (see Figure 6). The balance in a LEC gratis arrangement (Figure 6) is almost completely determined by the cumulative consumption, with the self-sufficiency being reduced to a noise in the linear relation. Even more telling is that, 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. The difficulty 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.

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, because the grid has the capacity to satisfy 100% of the demand at any time, it will have no purchaser among the households. 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 exactly the 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 (see Figure 7). 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 kickstart a set of tantalizing business opportunities.

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