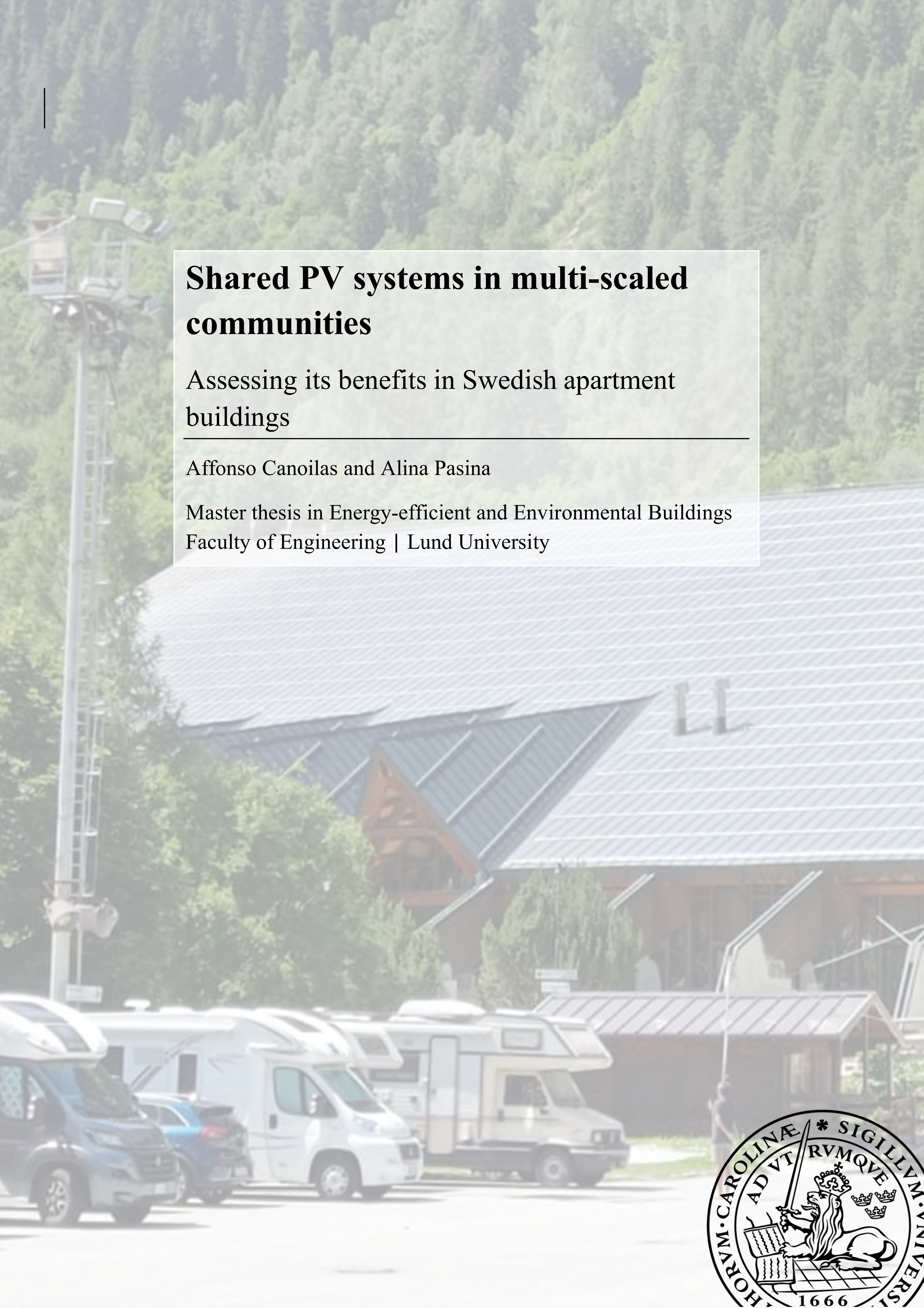

Shared PV systems in multi-scaled communities

Assessing its benefits in Swedish apartment buildings

Affonso Canoilas and Alina Pasina

Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and several research centers and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. Several departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280-degree programs and 2 300 subject courses offered by 63 departments.

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This international program provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behavior and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master program leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

In the past years, Sweden had been facing rapid growth of photovoltaic cells and total PV installation capacity increased from 300 kW to 1090 MW (2006-2020). To increase the number of PV users and therefore assist in achieving multiple sustainable goals regarding renewable energy, the installations of such systems were actively supported by the Swedish government. This project is aimed on evaluating the profitability of shared PV systems in communities of different sizes in Sweden. The current study used 1067 hourly measured electricity profiles of individual Swedish apartments to create multi-scaled communities with shared PV systems. The trading model was implemented to simulate electricity trading among prosumers in the community using Visual Basic Applications (VBA) in Excel. Further, the electricity costs were used for Life Cycle Cost assessment (LCC). The LCC results for shared PV systems were later compared to households that own PV individually and households that do not own a PV system to demonstrate the increase of profitability. The results were obtained for two locations in Sweden: Karlstad and Kiruna. The results portrayed the financial benefits of shared PV systems in comparison with individually owned PV systems.

Acknowledgement

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1. Introduction

The United Nations' seventh sustainable development goal describes several targets regarding clean energy, including the increase of the renewable energy share in the global energy mix. The Swedish government's goal is that 100 % of the country's electricity will come from renewable sources by 2040 (Zhong, Bollen, and Onnberg 2021). According to the official Statistic Database (SCB 2022b), Sweden's energy mix is mainly composed by hydro (43 %) and nuclear power (31 %). However, the recent decommissioning of nuclear energy opened space to increase the share of wind and solar power (Kan, Hedenus, and Reichenberg 2020). A strategy proposed by the Swedish Energy Agency was to increase the share of solar power to 10 % by 2040 (Swedish Energy Agency 2016).

Within solar power technology, the use of photovoltaic (PV) cells has been rapidly growing in Sweden since 2006. According to collected data by the National Survey of PV Power, Sweden went from 300 kW of PV capacity installed that year to nearly 1090 MW in 2020 (IEA - PVPS 2020). To increase the number of PV system users, the Swedish government has implemented support policies. Subsidies were provided to consumers to reduce the installation costs to help consumers with initial investment. Also, consumers would benefit from taxes reduction for selling the electricity surplus back to the grid (Palm, Eidenskog, and Luthander 2017).

This depicts how popular PV systems are becoming in the Swedish market. More homeowners are willing to invest in PV panels for a variety of reasons, including environmental concerns and mostly recently profitability (Palm 2018). In Sweden, retail electricity costs are still higher than the costs for self-produced electricity. Therefore, the use of self-produced electricity reduces the amount of purchased electricity, increasing the user's profitability (Luthander et al. 2015).

In several studies, (Luthander et al. 2015), (Bertsch, Geldermann, and Lühn 2017), (Radl et al. 2020), (Liu et al. 2017), the percentage of PV electricity that is used is referred as "self-use". It is calculated by dividing the used PV electricity by the total electricity production. A higher self-use increases the financial benefits for PV system users; however, their electricity use is far from being entirely covered by production.

The reality is, the users are mostly in need of electricity, when there is no natural source of light. Therefore, there is more electricity and heating being used during the winter. However, due to the shorter days, the PV production in winter season in Scandinavian countries is consequently low. Also, many households use electricity for electric appliances and lighting overnight when PV electricity production is zero. As a consequence, all that eventually leads to the mismatch of production and use in several periods.

The electricity use and production mismatch not only restrain financial gains for PV owners but also affects the electric grid's supply and demand balance. The consequences of supply and demand imbalance during the peak demand become crucial when lead to a high risk of electricity outage, creating additional challenges for electricity companies (Peng et al. 2020). Correspondingly, peak demand has an influence on selling and buying electricity prices and, in turn, it negatively affects PV owners (Carli et al. 2020). Despite on net-metering type, high demand causes significant increase of buying prices during high demand and reduction of the price for selling surplus electricity during production in low demand.

Hence, to ensure efficient grid operation, electricity supply and demand must be well-balanced (Lamnatou, Chemisana, and Cristofari 2022) The absolute balance can theoretically be attained by producing enough electricity during the peak hours while reducing overproduction. By increasing self-use, it allows users to make better use of their PV system. Nevertheless, this approach is hard to apply in reality without use of electricity storage. The main reasons are high load variations according to individual user behaviours and weather conditions. It becomes hard to predict situations considering those variables (Chaudhary and Rizwan 2018).

Other European countries addressed the grid's imbalance issue with a concept known as Smart Grid (Zhang et al. 2014). Basically, users started to apply electricity management technologies consisting of metering devices and sensors to circulate electricity use information between utility company and the users. As a result, it assisted utility companies in balancing electricity supply and demand, as well as users in reducing their electricity costs (Farhangi 2010).

Within the Smart Grid context, microgrids and energy communities' concepts were created. In simple terms, electricity consumers locally producing renewable energy, who were usually referred to as "prosumers", form a community to share PV electricity production (Mengelkamp et al. 2018). By aggregating the prosumers electricity demand, it allowed them as a community to use more self-produced electricity and rely less on grid's electricity (Reis et al. 2019).

The temporal difference of the combined electricity demands reduces the number of hours when PV electricity is not being used (Radl et al. 2020) (Reis et al. 2019). Given that, recent research on PV system sharing has been developing models to prove its applicability in real cases. These models treat an energy community as a trading zone. Basically, prosumers trade their electricity surplus with other prosumers in electricity shortage. To do so, these models count with an entity, known as aggregator, or Energy Sharing Provider (ESP) (Liu et al. 2018). This entity (e.g., third party company) intermediates the electricity trading between prosumers themselves and the utility grid. By being impartial, the aggregators can balance electricity supply and demand within a prosumers' community (Liu et al. 2017).

Previous research presented the advantages of sharing PV systems in a community when compared to individually owned PV systems. However, there is scant research about the increasing financial benefits of different communities' scales. Moreover, it is still lacking investigation about optimal PV system size when sharing within larger communities. These outputs can enhance PV dissemination in the market and policies' changes. The findings become important for a country with ambitious goals for renewable energy and decarbonization like Sweden.

1.1. State-of-the-art

As mentioned, previous studies analyzed investigated the possible benefits of shared PV systems. The literature review presented below gives a short description of those studies and shows the diversity in terms of methodology. While the results portrayed the financial improvements when sharing PV systems.

(Fina, Auer, and Friedl 2019) investigated the profitability of a community with shared PV systems. The study's case consisted of real measured electricity load profiles of few different settlements (Single-family houses, multi-apartment buildings, historical buildings, and commercial facilities). The settlements not only had different electricity-providing sources, but also roof top spaces and constrains for PV panels installation. The study determined the efficiency of an electricity sharing community for each type of settlement. Single-family houses profited more from the synergy of different load profiles and multi-apartment buildings presented the highest cost reduction within the settlement types.

Research made in Portugal (Ramos et al. 2021), where PV sharing is regulated, emphasizes the benefits of PV sharing, specially regards increasing self-use. It also explores different models of energy communities to share PV electricity. The proposed model in the paper consisted of an apartment building sharing PV electricity with the assistance of an energy aggregator to manage the distribution of electricity. The analysis considered the use of batteries to store part of the electricity not being utilized.

Moreover, (Reis et al. 2019) provides a study about load aggregation using electricity use data of 18 households and three small shops in Portugal. It revealed an improvement of self-use between 50 % and 80 % by just aggregating 10 households' loads and using a 1 kWh/kWp battery. Additionally, a 90 % self-use increase was reported when considering the small shops in the load aggregation. The study depicts the increase of self-use and profitability in relation to individually owned PV systems.

(Radl et al. 2020) compared eight countries (Austria, Germany, Netherlands, Belgium, France, Italy, Spain, and Portugal) in terms of cost reduction when forming an energy community where PV electricity is sharable. In the study, two scenarios were analyzed. The first one included carbon-based society, where energy for producing heat and operating transportation were provided by fossil-fuels. The second one represented a full-electric scenario which considered the use of heat pumps to provide heat and electric-vehicles as the main transportation. This last scenario presented higher electricity use tough. Using simulated load profiles, the results presented energy costs reduction for all countries when implementing PV system, and even higher costs reduction when sharing PV systems. With high electricity prices in countries like Germany, Belgium, and Netherlands, PV system's sharing becomes even more profitable through increased self-use of PV electricity.

(Liu et al. 2018) proposed three different models for peer-to-peer (P2P) electricity trading in a microgrid using PV electricity. The models, so called bill-sharing, Mid-market rate, and action-based pricing, were composed of different pricing rules for trading electricity. The study shows that it was possible to reduce electricity costs up to 30 % using any of the proposed P2P electricity trading models, and the main driver for such reduction was the diversity of load schedules. Also, the study concluded that the use of P2P electricity trading can be used for residential microgrids in large scale.

Within the same topic (Liu et al. 2016) and (Liu et al. 2017), proposed models of PV sharing integrated with Demand-Side Management, a Smart Grid approach to manage electricity demand. The microgrids worked as electricity trading zones with internal electricity prices. These internal prices could change according to the electricity supply and demand ratio of the microgrid. Both presented models that resulted in positive revenue when compared with direct electricity trading between PV prosumers and utility grid.

1.2. Electricity regulations in Sweden

To ensure the smooth integration of shared PV systems, many performed studies were discovered that offer re-assessment and adjustment of legislation regarding smart grid systems according to Swedish regulations.

As follows, one problem was found is no legal support for sharing PV system between multiple households in Sweden. Which according to (Parks and Wallsten 2020), is caused by two factors: taxes and rental laws. In regard to current regulations, allowing PV owners sharing electricity with neighbors could require changes in regulations for taxation. According to the current regulations, electricity tax must be paid by everyone using electricity from the main grid. In the case of shared PV systems, it would create additional complications regarding electricity tax because prosumers would be using electricity from another household in their community and the main grid.

The similar issue arises if calculating electricity certificate fee for each user that is a part of shared PV system community. The existing electricity certificates create an additional financial benefit for individuals who decide to make decisions towards green electricity production, as they can measure their production and then sell their certificates to electricity trading companies. Subsequently, electricity certificates are then being sold to electricity companies who are subject to quota obligations due to their production of unclean electricity. The cost paid for those certificates is then blended as a fee in users' electricity bill. In case of shared PV systems, due to lack of legal ability to track certain type of electricity use, it becomes questionable, whether some individual users must pay the electricity certificate fee or not. According to (Lisberg Jensen Malte von Utfall Danielsson Carl 2017), the only solution to solve this issue at the current stage is to stop selling electricity certificates to PV owners or if municipalities would buy it instead. However, neither electricity companies nor the city government had planned to make such a significant financial contribution to support electricity sharing.

Finally, sharing PV electricity could conflict with rental laws, as present situation states, private house renters have the right to choose their electricity supplier. Meaning that shared PV systems could not be legally applied to rented housing units (Energimarknadsbyran 2016).

Another problem reveals the lack of incentive from the government since existing regulations provides no financial support to electricity network companies and PV owners regarding smart-grid systems (Lisberg Jensen Malte von Utfall Danielsson Carl 2017). Therefore, introduction of policies that would strengthen incentives are required for successful integration. The possible improvement to reinforce the incentives was proposed by the author: implementing dialogue-based regulation between electricity network companies and the authorities.

The suggestion represents a dialogue-based regulation that calls for more active cooperation of governmental authorities and electricity network companies.~~,~~ According to (Lisberg Jensen Malte von Utfall Danielsson Carl 2017), there must be a place for more open communication processes where two parties discuss and agree on objectives for network operation. Also, electricity companies can develop their own proposals for how the goals proposed by the authorities could be achieved. Indeed, such an approach would need strong cooperation from both parties (electricity companies and authorities), but it provides a number of benefits such as greater freedom to plan achievement of different goals and therefore invest into innovative technical solutions.

1.3. Aim & objectives

The main goal of this research is to demonstrate the profitability of shared PV systems. As study was divided into two parts, the first objective was to calculate electricity balance and trading for each randomized combination of electricity use profiles. The second part was focused on determining Life Cycle Costs for households and comparing themselves in different situations: when sharing a PV system, own PV system individually and without any PV system.

The results, methods and approaches provided in this study could be used to evaluate the potential profitability for various combined electricity use profiles at international level.

1.4. Limitations

Despite there are many building types such as commercial, residential, or educational, the current study was fully focused on residential apartment buildings, as pre-measured data represents individual apartment blocks. In addition, it is worth to note that only PV systems without battery/storage system were considered in this research.

The current work accounts for certain degree of uncertainty due to the assumptions such as weather forecasts and user-dependency of the electricity use profiles that were initially used. Additionally, due to limitations of program used for main calculations, the number of combinations and samples for larger communities were reduced. Even though this could represent a small decrease in the results accuracy, it did not change the main behaviour of the results.

PV electricity supply was simulated assuming PV modules with tilt and azimuth of, respectively, 20 ° and 180 °, in both Swedish locations: Karlstad and Kiruna. Although, those values could be optimized to reach a slightly higher PV electricity supply. All in all, the values were kept the same in the simulations for both locations. Together with that, the PV models' depreciation was not accounted.

1.5. Hypothesis

Two hypotheses for the current study were formulated and presented such as:

1. Sharing PV systems' electricity is significantly more profitable when compared to the individually owned PV systems.

2. By increasing the size of community with shared PV systems, the profitability of participating households is growing.

2. Methodology

The following methodology section presents a detailed step-by-step of the entire process needed to calculate profitability of shared PV systems (Figure 1). Using Visual Basic Applications (VBA) in MS Excel, randomized combinations from a database of 1 067 households were created. The profiles come from real measurements made in previous research (Bagge, Lindstrii, and Johansson 2012) . A more detailed description of the profiles was given in section 2.1.

The household electricity profiles in each combination were further matched with simulated PV supply for multiple PV systems with different sizes using SAM software (NREL 2022). The locations chosen for those simulations: Karlstad and Kiruna. The reason behind the location's choice was described in Section PV electricity 2.2.

Further, based on the electricity balance calculations (section 2.5), an electricity trading scheme was applied to calculate exchange of electricity among prosumers and their electricity costs (section 2.6). LCC was then calculated for each household sharing PV system within a community. LCC was also calculated for the same households when owning a PV system without sharing and without a PV system. The LCCs were then compared to determine the profitability in different situations (sharing, not sharing, and without PV system).

Finally, average profitability and payback for different sized communities and different PV systems were displayed in the results section. The sensitivity analysis was performed for a different electricity price growth rate and the inclusion of tax reduction for individually owned PV systems. In addition, to observe the impact of the weather, the results for Karlstad were compared results for with Kiruna.

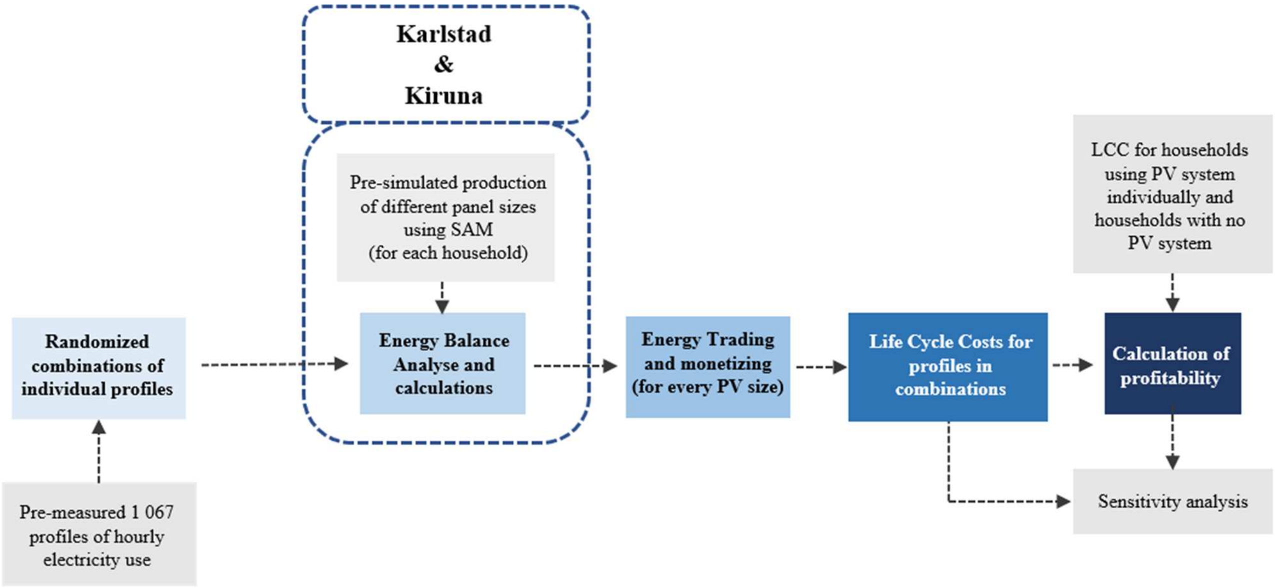

Figure 1 - Methogolody chart.

2.1. The household's electricity profiles

The data used for the current study consisted of pre-measured household electricity use profiles for individual households by (Bagge, Lindstrii, and Johansson 2012) that were presented and analysed as a part of previously performed research (Fransson 2020). The measurements of electricity and domestic hot water had been collected during the year of 2012 from 1 509 apartments of different sizes in several buildings in Karlstad. However, the gathered data needed to be studied and verified. During inspection, several errors and strange patterns were detected such as profiles with more than 3 % of missing data or other anomalies like very high averages or inexplicable spikes (Fransson 2020) Therefore, according to (Fransson 2020), a part of the measured profiles needed to be discarded. Finally, only 1 067 profiles that passed 3 % missing data limit and visual inspection were verified and therefore included into the initial dataset of the current work.

According to (SCB 2022b), the population of Karlstad municipality is demographically-representative of Sweden. The measured data was sorted by apartment sizes in m^2 and number of rooms, between 1 and 4. Approximately 75 % of the apartments contained two or three rooms and the kitchen, the rest of 25 % belongs mainly to 5-rooms apartments with the kitchen, with just a few 6-rooms apartments. The household electricity usage included electricity for light, electrical appliances, and equipment, along with electric towel rails in the bathrooms. In addition, all households had access to shared laundry room in the building or neighbourhood.

The results demonstrated that the general usage of electricity was higher on Saturdays and Sundays when most people are typically free from work or university and are expected to be present at home more hours than on weekdays. However, the large spread in measured electricity uses and indoor temperature in different apartments was found, where high usage occurred in relatively few apartments. One of the conclusions of the study was the average use of household electricity increases both with increased apartment area and number of rooms. However, weak relationships were noticed while closely comparing same size apartments, since there were significant differences in usage. It is mainly explained by strong relation to different user-behaviours that are fully impacted by habits and values of individuals. Authors that measured data (Bagge, Lindstrii, and Johansson 2012) concluded that there was no correlation between received household electricity profiles and apartment sizes was considered in the current research, nor further conclusions were made basing on the area of the households, as the usage of electricity was previously proved to be related to individual human behaviours.

2.2. PV electricity supply

In this study, the System Model Advisor program (NREL 2022) was used to simulate hourly supply of PV electricity for a whole year. Karlstad's weather data was chosen to correspond with the location of the households that had their electricity use measured. However, solar radiation varies considerably in different regions of Sweden. In the South, radiation can reach a maximum of 1 050 kWh/m^2, meanwhile in the North, radiation can go as low as 750 kWh/m^2 (SMHI 2017).

To demonstrate the impact of weather on the PV system's profitability, electricity supply was also simulated for another location representing the north of Sweden. Thus, Kiruna' weather data was chosen for this purpose. In section 3.2, results of electricity supply with the same PV system in three different locations in Sweden were shown.

In this study, the assumption was that all households within a community had the same PV system size, and they decide to share their electricity surplus within the community. Hence the term "shared PV systems" in this paper. Initially, the supply of several PV system sizes was simulated and combined with every single household electricity profile. All combinations were then evaluated based on the amount of electricity demand covered by electricity supply and the system's costs. In the end, four sizes (0.25 kWp, 0.5 kWp, 0.75 kWp, and 1 kWp) with the best results were chosen to be applied for each household of the combinations. The configuration for PV systems were modules with 20 % efficiency. The modules were tilted in an angle of 20 ° and with azimuth of 180 ° to maximize supply in summer in Karlstad. Although this system configuration could be optimized for Kiruna, the values were kept the same in both locations since the aim was to compare results with different weather only.

2.3. Statistical approach for sampling

In this study, household electricity profiles were combined using random selection. Different combination sizes were made regarding the number of households being combined (e.g., 2, 5, 10 households). For each combination size, the term "population" refers to all possible combinations that can be made with the 1 067 household electricity profiles and the term "sample" refers to a single combination. The total number of combinations that can be possibly created is extremely large. Thus, it becomes unviable to analyse distribution or variability of the whole population, due to lack of time and/or computational resources. It is more reasonable to employ sampling than census, which involves analysing the entire population and is more suitable for small groups (Israel 1992b).

A statistical theory called probability sampling was used to determine the number of samples needed for the analysis. It means that every combination in the population, has a non-zero chance of being selected (Israel 1992a), thus, the sample is completely aleatory.

However, this brings the issue of choosing a sample size large enough to represent the whole population statistical characteristic. Statistical formulas were developed to determine the sample size for large populations (Israel 1992a). One of these formulas is denominated Yamane formula (1), in which a desired margin of error is used to decide the number of samples, considering that the population standard deviation is unknown.

$$n = \frac{N}{1+N \cdot e^2} \qquad (1)$$

In equation (1), the number of samples is symbolized by "n", the population by "N" and "e" represents the desired margin of error. As it shows in Figure 2, for larger populations, the equation result is mainly influenced by the chosen margin of error, and it does not change from 400 samples. Keeping in mind that two electricity profiles are the bare minimum that can be combined, and the idea that repeated selection is allowed, i.e., selecting a repeated electricity profile in the same combination, there are more than 8 000 possible combinations. Hence, 400 samples were chosen to suit the study's time and computational limitations

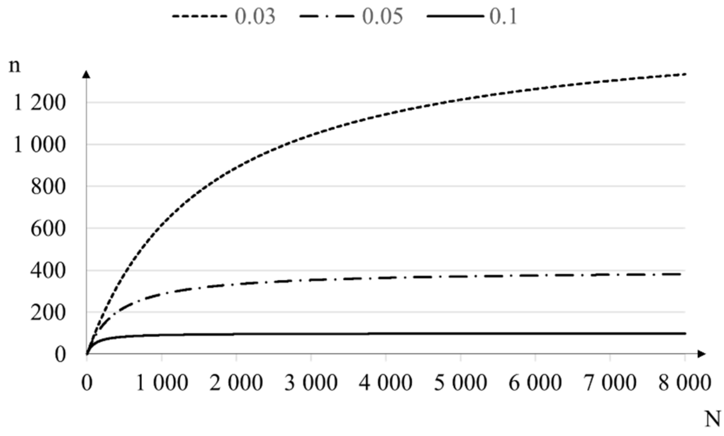

Figure 2 – Correlation of number of samples and population size using Yamane's equation with three different margins of error (0.03, 0.05, 0.1).

2.4. Randomized combinations

The random selection method was used to create the household combinations (Figure 3). The combinations were performed using VBA-coding application in MS Excel.

The number of combined households was determined through a quick manual trial-and-error process. According to previously presented hypotheses, it was expected to obtain results that demonstrate an increase in profitability as the number of households in the combinations increased. The trendlines for multiple different number of combined households were evaluated and numbers of combined households that appeared to be the most suitable for analyses were selected. It was crucial to detect the change between different sizes of combinations while still being able to observe the clear trend between the results. The process started with the smallest combination of 2 households and the number was further increased, according to the results from previous combination. Finally, the combination sizes were set to be for 2, 5, 10, 20 and 50 households.

All household profiles from the initial database were included in a randomization process. By using a random selection function, the necessary number of participants was grouped into one combination by randomly selecting profiles from the available database of 1 067 electricity use profiles (Figure 3). The total population of profiles was considered for selection in every independent run of the randomisation process, so previously selected profiles were free to be selected for multiple runs. Randomization was finalised by creating a database with all created combinations.

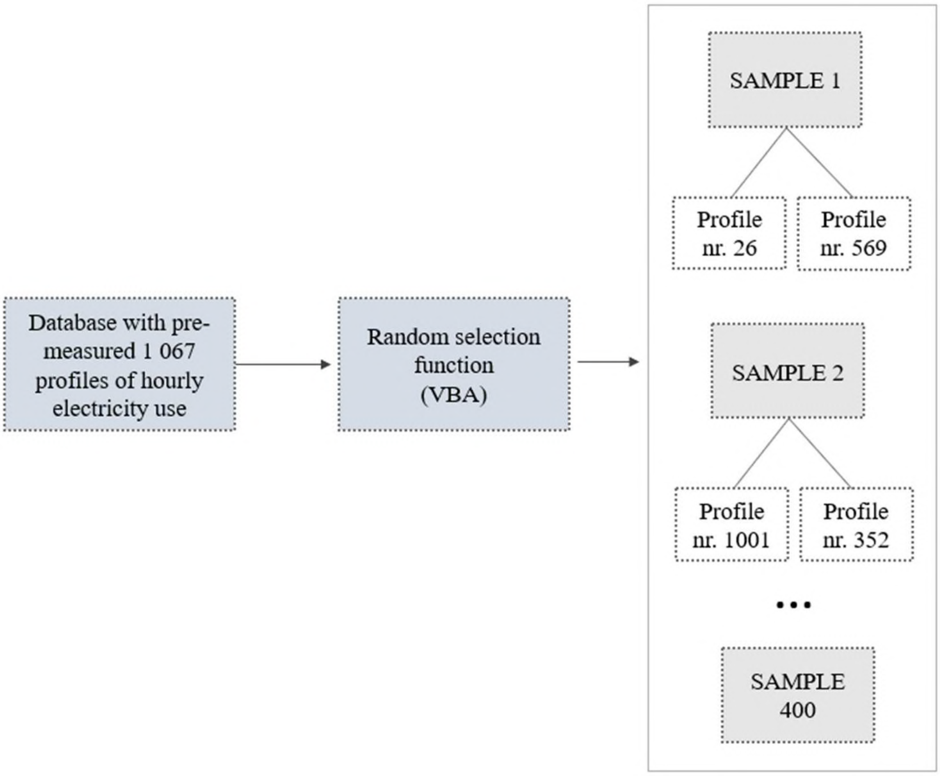

Figure 3 - Process of randomization using VBA-coding application in Excel. Example for building combinations, i.e., samples of 2 households.

2.5. Electricity Balance

Figure 4 shows an example of hourly household electricity together with PV electricity supplied along 24 hours in a day. From the chart, it can be observed two curves: the household electricity uses and PV electricity supply, in which the hourly difference between these curves is called Electricity Balance (EB).

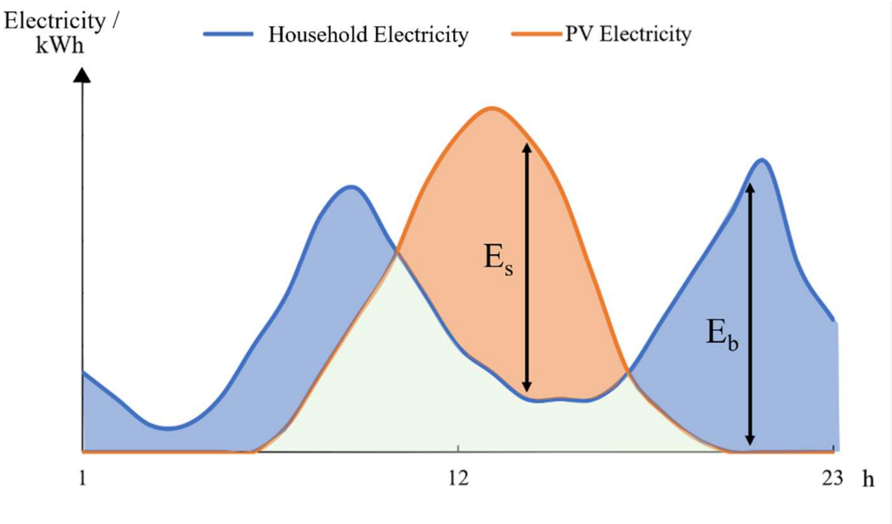

Figure 4 – Household electricity use and supply of a household. The curves difference represents bought and sold electricity.

In each hour (t), the electricity balance, denoted by EB(t), was calculated for an individual household referred as n using equation (2). The supplied PV electricity was considered as P(t) and the used household electricity as E(t). When the equation result is negative (-), it depicts electricity that needs to be bought import (E_b) (equation 3). When the result is positive (+), it depicts surplus of electricity that could be sold (E_s) (equation 4). Moreover, if the result is equal to zero, it means that the PV electricity supply matched the electricity use.

$$EB_n(t) = P_n(t) - E_n(t) \tag{2}$$

$$E_{b\,n}(t) = \begin{cases} -EB_n(t), & EB_n < 0 \\ 0, & EB_n \geq 0 \end{cases} \tag{3}$$

$$E_{s\,n}(t) = \begin{cases} 0, & EB_n \leq 0 \\ EB_n(t), & EB_n > 0 \end{cases} \tag{4}$$

Every single household from the 1 067 was coupled with a PV system. This was done for the PV systems of size 0.25 kWp, 0.5 kWp, 0.75 kWp and 1 kWp. Last and most importantly, the electricity balance was calculated for all 8 760 hours of the year for each household with the previously mentioned PV systems.

2.5.1. Sold electricity to the main grid

To observe the change in self-use in combinations of different sizes, an average sold electricity to the main grid for an individual household was calculated. The calculations were performed for 0.5 kWp PV system. By applying the method presented previously, hourly electricity balance of each household that participate in the combination was calculated individually. Furthermore, using this data, the total sum of sold (${E^{group}}_s(t)$) and bought (${E^{group}}_b(t)$) electricity from all individual households participating in each combination was found for each hour (t), using equations 5 and 6.

$$E^{group}{}_{s}(t) = E_{s\,1}(t) + E_{s\,2}(t) + \ldots + E_{s\,N}(t) \quad (5)$$

$$E^{group}{}_{b}(t) = E_{b\,1}(t) + E_{b\,2}(t) + \ldots + E_{b\,N}(t) \quad (6)$$

where,
N – corresponding number of every household in the combination who needs to sell or buy electricity
$E_{s\,N}(t)$ – the amount of electricity that a household can sell in certain hour
$E_{b\,N}(t)$ – the amount of electricity that a household needs to buy in certain hour

To calculate the total hourly amount of sold electricity to the main grid as the community ($E^{group}{}_{s\,grid}$), the equation 7 was applied:

$$E^{group}{}_{s\,grid}(t) = E^{group}{}_{s}(t) - E^{group}{}_{b}(t) \quad (7)$$

The sold electricity to the main grid per individual household was further calculated by extracting an average from all samples for a certain combination size.

2.6. Electricity Trading

Households sharing PV systems can have financial advantages when trading electricity with each other. Trading can not only reduce their costs of purchased electricity, but it can also increase their profits for sold electricity. Figure 5 and Figure show, respectively, examples of households purchased electricity costs and sold electricity gains when trading electricity with other households.

Households in electricity shortage can buy electricity surplus from other households. This electricity is bought at a lower price than that offered by electricity companies. Thus, households can reduce their electricity costs when trading. Figure 5 shows an example of it, where the solid blue line represents the amount of electricity traded between households in that time of the day. The dashed orange line represents the electricity cost of one the households when it is not trading electricity with other households, meanwhile the dashed blue line represents the electricity cost of the same household when trading electricity with other households.

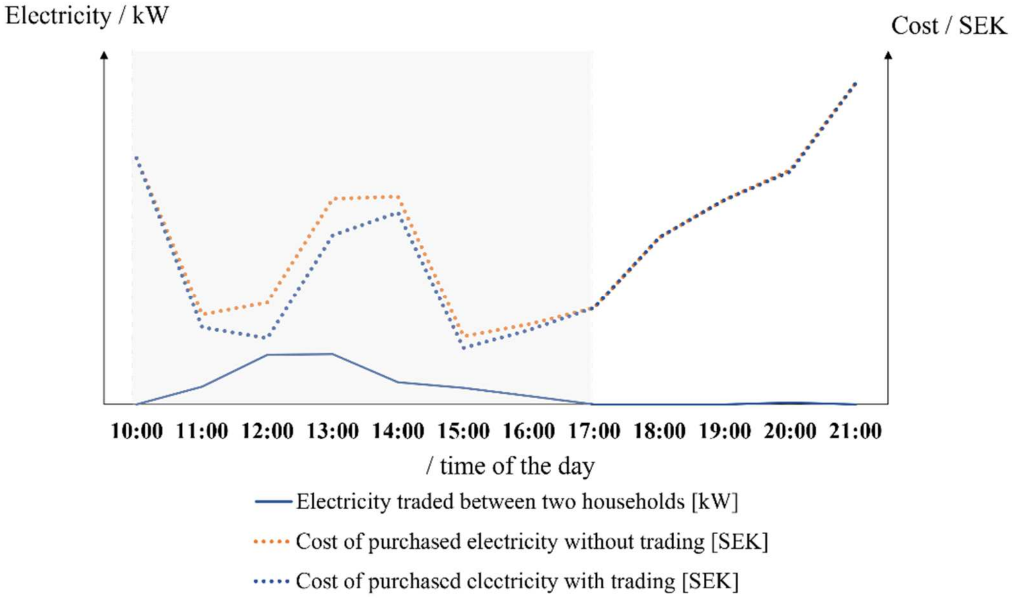

Figure 5 - A household's hourly costs of purchased electricity. The cost reduces when trading electricity with another household. Tax reduction was not included.

On the other hand, households with electricity surplus can offer it to other households at higher prices than those offered by electricity companies. As a result, their profits from selling electricity increase when they trade, as it is shown in Figure 6.

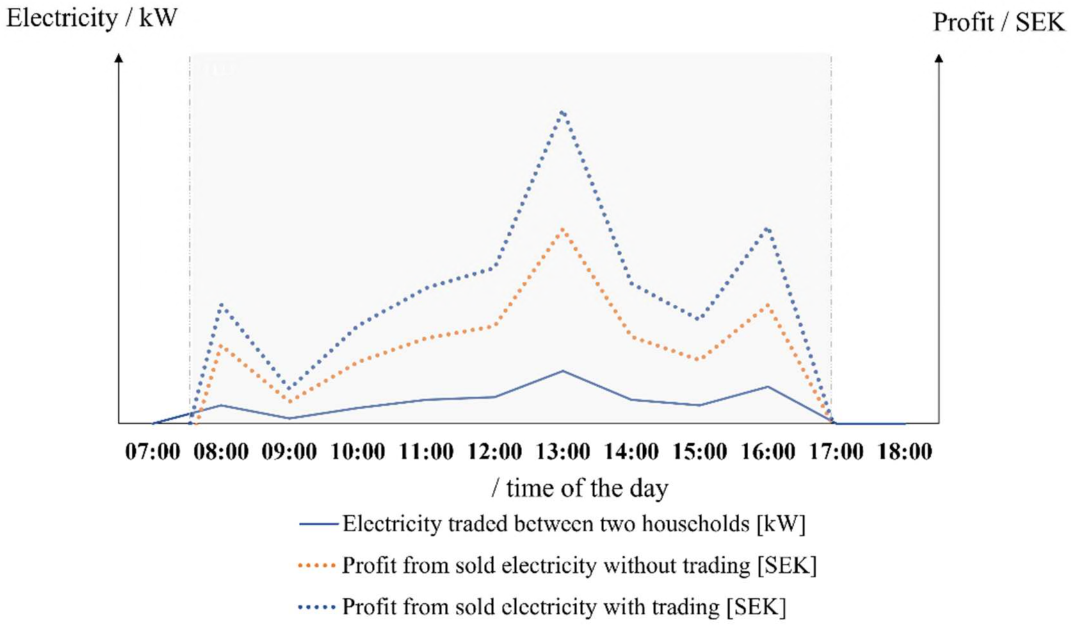

Figure 6 - A household's hourly profit from sold electricity. The profit increases when trading electricity with another household. Tax reduction was not included.

A price model proposed by (Long et al. 2018), so called Mid-Market rate, was used to calculate the electricity costs for an individual household, referred as *n* ,when trading electricity within a community. Considering the electricity user's perspective, three prices were considered in the model's calculation: the price to buy electricity from the electricity grid (Pr_{bg}), to sell electricity to the electricity grid (Pr_{sg}) and the price of buying or selling electricity from and to other households (Pr_c). In the model, Pr_c is assumed as the average of Pr_{bg} and Pr_{sg}. Figure 7 shows the price scheme with an example of a three-household community trading electricity.

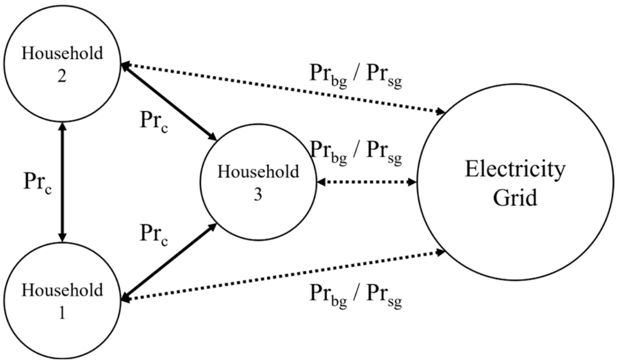

Figure 7 - Example of electricity trading between three-household community and the main electricity grid.

A community's electricity offer and demand means, respectively, the total amount of electricity surplus and electricity that must be purchased considering all the households in the community. In different hours, the offer and demand for electricity within a community can vary. If the community's electricity offer matches its demand, all the electricity can be traded amongst households at the trading price (Pr_c). However, when the offer is higher than demand, the whole amount of electricity surplus cannot be traded amongst households. Some part must be sold to the grid at the grid's price (Figure 8). The same happens for the purchased electricity in the opposite situation when demand is higher than the offer. Part of the electricity will be purchased from other households, while part will be purchased from the grid (Figure 9).

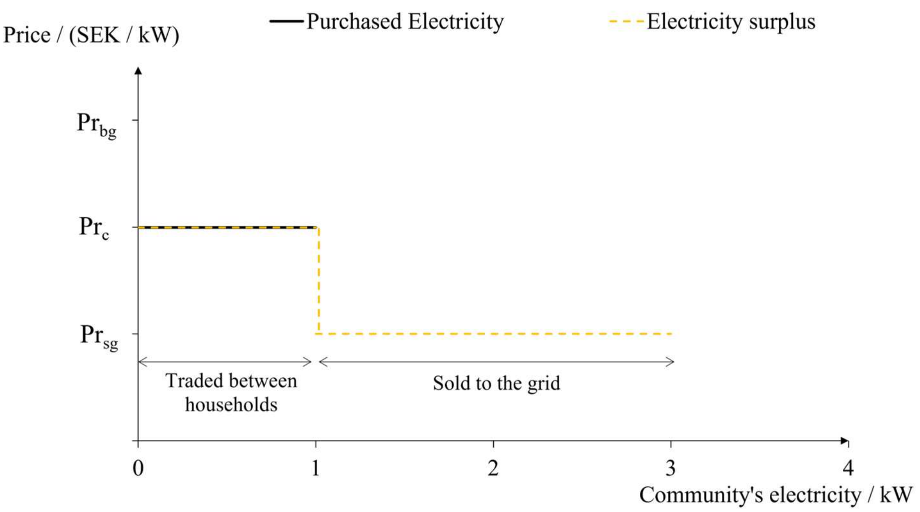

Figure 8 - Example of electricity pricing in a community of households when offer is higher than demand.

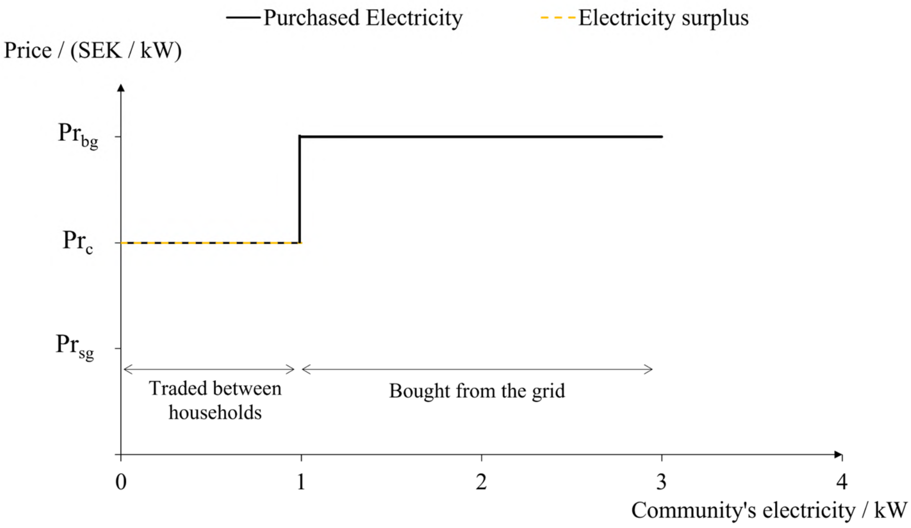

Figure 9 - Example of electricity pricing in a community of households when demand is higher than offer.

Therefore, the price that homeowners would have to pay for electricity, referred as Pr_b, or sell their electricity surplus, referred as Pr_s, would depend on the electricity offer and demand at that moment.

At a certain hour *t*, if the community's electricity offer and demand are equal, then Pr_b and Pr_s are equal to Pr_c as it is shown in equation 8.

$$Pr_b(t) = Pr_s(t) = Pr_c(t) \tag{8}$$

If the electricity offer is higher than demand, then Pr_b is equal to Pr_c (equation 9). Whereas Pr_s is a proportion of Pr_c and Prsg, as it is shown in equation 10, where N is the total number of households in the community.

$$Pr_b(t) = \ Pr_c \tag{9}$$

$$Pr_s(t) = \frac{\sum_{n=1}^{N} E_{b\,n}(t) \times Pr_c + \left(\sum_{n=1}^{N} E_{s\,n}(t) - \sum_{n=1}^{N} E_{b\,n}(t)\right) \times Pr_{sg}}{\sum_{n=1}^{N} E_{s\,n}(t)} \tag{10}$$

If the electricity demand is higher than the offer, then Pr_s equal to Pr_c (equation 11). While Pr_b is a proportion of Pr_c and Pr_{bg}, as it is shown in equation 12, where N is the total number of households in the community.

$$Pr_s(t) = Pr_c \tag{11}$$

$$Pr_b(t) = \frac{\sum_{n=1}^{N} E_{s\,n}(t) \times Pr_c + \left(\sum_{n=1}^{N} E_{b\,n}(t) - \sum_{n=1}^{N} E_{s\,n}(t)\right) \times Pr_{bg}}{\sum_{n=1}^{N} E_{b\,n}(t)} \tag{12}$$

Finally, having determined the real prices to buy and sell electricity, the hourly electricity cost, EC(t), for a household *n*, was calculated as in equation 13.

$$EC_n(t) = \begin{cases} E_{b\,n}(t) \times Pr_b & EB_n < 0 \\ -E_{s\,n}(t) \times Pr_s & EB_n > 0 \end{cases} \tag{13}$$

An example of how electricity cost is calculated for each household in a three-household community is shown in Table 1 and Table 2. Table 1 displays the example of electricity cost calculation when electricity offer is higher than demand. Household 1 purchased electricity from the other two households at 1.5 SEK / kW, which resulted in 3 SEK of cost for its electricity. Meanwhile, household 2 and 3 had to share proportionally the electricity being sold to Household 1, shown as A, and the electricity being sold to the grid, shown as B. As a result, household 2 and 3 had, respectively, 4.4 SEK and 6.6 SEK of profit with sold electricity.

Table 1 - Example of electricity cost calculation in a three-household community when electricity offer is higher than demand.

	Electricity purchased E_b / kW	Electricity surplus E_s / kW	Selling or buying price amongst households Pr_c / (SEK / kW)	Price to sell to the grid Pr_{sg} / (SEK / kW)	Electricity Cost EC / SEK
Household 1	2	0	1.5	1	$2 \times 1.5 = 3$
Household 2	0	4	1.5	1	$-\frac{4}{10} \times 2 \times 1.5 + (10-2) \times 1 = -4.4$
Household 3	0	6	1.5	1	$-\frac{6}{\boxed{10}} \times \overset{A}{\boxed{2 \times 1.5}} + \overset{B}{\boxed{(10-2) \times 1}} = -6.6$
Total	2	10	1.5	1	$2 \times 1.5 + (10-2) \times 1 = 11$

$$Pr_s(t) = \frac{\overset{A}{\boxed{\sum_{n=1}^{3} E_{b\,n}(t) \times Pr_c}} + \overset{B}{\boxed{\left(\sum_{n=1}^{3} E_{s\,n}(t) - \sum_{n=1}^{3} E_{b\,n}(t)\right) \times Pr_{sg}}}}{\boxed{\sum_{n=1}^{3} E_{s\,n}(t)}}$$

In Table 2 displayed an example of electricity cost calculation when electricity demand is higher than offer. Household 1 sold electricity to the other two households at 1.5 SEK / kW, which resulted in 1.5 SEK of profit for its electricity. Meanwhile, household 2 and 3 had to share proportionally the electricity purchased from household 1, shown as A, and the electricity purchased from the grid, shown as B. As a result, household 2 and 3 had an approximate electricity cost of, respectively, 1.8 SEK and 3.7 SEK.

Table 2 - Example of electricity cost calculation in a three-household community when electricity demand is higher than offer.

	Electricity purchased E_b / kW	Electricity surplus E_s / kW	Selling or buying price amongst households Pr_c / (SEK / kW)	Price to buy from the grid Pr_{bg} / (SEK / kW)	Electricity Cost EC / SEK
Household 1	0	1	1.5	2	$-1 \times 1.5 = -1.5$
Household 2	2	0	1.5	2	$\frac{2}{6} \times 1 \times 1.5 + (4-2) \times 2 \cong 1.8$
Household 3	4	0	1.5	2	$\frac{4}{\boxed{6}} \times \overset{A}{\boxed{1 \times 1.5}} + \overset{B}{\boxed{(4-2) \times 2}} \cong 3.7$
Total	6	1	1.5	2	$1 \times 1.5 + (4-2) \times 2 = 5.5$

$$Pr_b(t) = \frac{\overset{A}{\boxed{\sum_{n=1}^{3} E_{s\,n}(t) \times Pr_c}} + \overset{B}{\boxed{\left(\sum_{n=1}^{3} E_{b\,n}(t) - \sum_{n=1}^{3} E_{s\,n}(t)\right) \times Pr_{bg}}}}{\boxed{\sum_{n=1}^{3} E_{b\,n}(t)}}$$

2.7. Initial data settings for LCC

Further, the financial assessment was carried out to monetize expenses and income for households that participated in combinations, in each case. Life Cycle Costs calculations were performed for a period of 40 years. The scope of analysis included initial investment, maintenance, and electricity costs.

Initial investment costs covered installation expenses and the cost of inverter, meter, and PV system (Table 3). The prices were based on the market situation, according to (IEA - PVPS 2020). The maintenance costs included the prices for changing inverters and PV modules. The maintenance period for inverter was set to be 10 years, and for the PV modules was 25 years. The initial and maintenance costs were calculated individually for each household considering a size of their PV system, either they are a part of the community or not. It means that in case of shared PV systems, the initial and maintenance costs were not shared between participants.

Table 3 - Investment and maintenance costs.

	Life Cycle Costs	TOTAL Costs / (SEK / kWp)
Initial costs	PV systems installation	16 090
	PV system costs	
	Inverter	
	Meter	
Maintenance	Inverter change	2 040
	PV modules change	3 170

Electricity costs included running costs for bought electricity and already accounted the gains with sold electricity. The cost of bought electricity had multiple choices for scenario development. Between 2019-2020, Swedish electricity market went through many changes that affected electricity prices, if compared to the past years. Since 2020, along with increase of electricity prices, a significant difference in prices between north and southern regions in Sweden could now be seen. It was mainly caused by shutting down nuclear power stations in Southern Sweden, while renewable power stations in the North remained operating (Lithner 2021). As followed, longer electricity transportation distances from North to South contributed to high competition in prices. Also, most of the municipalities in the North are currently paying reduced electricity tax, as northern regions supply and use more renewable electricity (Skatteverket 2022a).

Therefore, it was decided use hourly spot prices from 2019, since the similar prices between north and south of Sweden allowed to analyse impact of the weather on the results. What is more, it reflected the further distribution of renewable electricity sources as an alternative to help reaching governmental goal to decommission all nuclear power stations in the country by 2045 (IEA 2019). Since the Swedish government is trying to extend alternative power sources, it is assumed that more wind, hydro- and, in particular, solar power installations would be built in the next years. As an example, in 2019 Vattenfall government-owned electricity company set a goal to upgrade their hydropower stations and increase capacity by 600 megawatts by 2023 (Vattenfall 2020). Upgrading and implementing additional electricity sources, not only contributes to decrease the electricity price difference between regions but to potentially reduce the average electricity price in Sweden.

The spot price was given hourly (Nord Pool 2022) In addition, all trading and network fees were calculated and added hourly based on the current costs from the biggest electricity providers in each region. It is worth to note, that only variable electricity contract was considered, as it allowed for more transparent data from electricity providers (Table 4). In order to make assumptions of growth rates for upcoming years, the average of electricity trading and network prices per region were calculated, based on data from past years (2016-2020) (Energimarknadsbyran 2022). The prices for sold electricity was identical to hourly spot price according to the chosen year. As it was mentioned before, the chosen scenario of 2019 implied even prices in both regions.

Table 4. Inputs of hourly electricity prices and growth rates, according to price scenario of 2019.

Electricity zone	Electricity provider	Type of trading/network fees included	Electricity price Scenario 2019	Price Growth rate
SE 1 (KIRUNA)	Vattenfall*	Fixed	0.0205 (SEK/hour)	2%
SE 3 (KARLSTAD)		Variable	0.31 (SEK/kWh)	

*Vattenfall: https://www.vattenfall.se/foretag/kundservice/amne/faktura-och-betalning/fakturaforklaring/
*Energimarknadsinspektionen: https://www.ei.se/sv/statistik/statistik-inom-omradet-el/Statistik-om-elhandel/historiska-jamforpriser-pa-elhandelsavtal/
* All prices include VAT 25%

In the current tax system of Sweden, the subsidies for PV ownership are an important tool to create awareness of the potential and value of PV systems (IEA - PVPS 2020). However, it was hard to make predictions over the years since tax reduction rules could change over time according to governmental goals (IEA - PVPS 2020). Therefore, the LCC calculations initially excluded tax reduction, to keep results more independent from further governmental decisions about subsidies. However, the current tax reduction measures were further included in sensitivity analysis.

In addition, the option for selling electricity certificates was not considered in this study. Current average price on the market (SolarSvea 2022) for 1 MWh sold electricity is 0.1 SEK/MWh. Besides that, the annual membership fee of 200 SEK/year must be paid by every micro-producer.

The interest rate was calculated based on the data from previous years (2016-2019), before the corona pandemic had a significant impact on the inflation. According to the statistical database from (SCB 2022b), the interest rate, based on years 2016-2019, in Sweden was 1.9 %. The maintenance cost growth rate was assumed to be 2 %, based on the consumer price index (CPI) from previous years (SCB 2022a).

2.8. Sensitivity analysis

The sensitivity analysis for LCC was performed, to observe the impact of different scenarios. The first change was made to the electricity price growth rate. It was interesting to observe change with a slight increase to 3 % (SCB 2022b), assuming scenario where electricity become more expensive. Another change included a tax reduction that was applied to individual PV owners, while comparing them to the situation when they share PV system and do not account for tax reduction. According to current situation in Sweden, PV micro producers that produce a maximum of 43.5 kW while sell less electricity than they consume from the main grid, are accounted for a tax reduction of 0.6 SEK/kWh, that is added on the top of their income from selling surplus electricity to the main grid (Skatteverket 2022b). Other tax reduction measures as ROT deduction and tax reduction for Green Technology were excluded from calculations in this study.

2.9. LCC calculation

For a household, referred as n, the LCC was calculated considering the PV system investment cost (C_{inv}), the system's maintenance (C_{main}) and the annually bought electricity ($C_{el.bought}$). The annual bought electricity cost was determined by just summing the electricity costs of all 8 760 hours, as it is shown in equation 14. Hence, by considering a certain number of years (Y) and using an interest rate (i), an electricity price growth rate (g) and a maintenance cost growth rate (m), the net present value (NPV) for the cashflows C_{main} and $C_{el.bought}$ can be calculated as it shown in equations 15 and 16. Finally, the LCC was the sum of the investment cost and the NPV for maintenance and bought electricity cost as it is shown in equation 17.

$$C_{el.bought\ n} = \sum_{t=0}^{8760} EC_n(t) \tag{14}$$

$$NPV_{main\ n} = C_{main\ n} \times (1+m) \times \frac{(1-(1+m)^Y \times (1+i)^Y)}{i-m} \tag{15}$$

$$NPV_{el.bought\ n} = C_{el.bought\ n} \times (1+g) \times \frac{(1-(1+g)^Y \times (1+i)^Y)}{i-g} \tag{16}$$

$$LCC_n = C_{inv\ n} + NPV_{main\ n} + NPV_{el.bought\ n} \tag{17}$$

2.10. Profitability

To evaluate the financial advantages of having a PV system individually or sharing it as a part of the community, the profitability was calculated.

The profitability is defined to be a profit that was received when the time to recover investment was shorter than the project's lifespan. The calculation method was applied to compare different scenarios and draw the difference between single households that were a part of shared PV community, own PV individually without sharing, or not using PV at all. It was implemented through the formula that extracts the difference between LCC costs and therefore validates the potential savings of choosing one scenario over another, as it was presented in the equation 18.

$$Profitability = LCC_{withPV} - LCC_{noPV} \tag{18}$$

where,
$LCC_{indiv.}$ – Life Cycle Costs for a single household who own a PV system
LCC_{noPV} – Life Cycle Costs for single households, who do not own a PV

To establish the common ground, LCC for a case with no PV system (LCC_{noPV}) was chosen. It was further compared either with LCC (LCC_{withPV}) of household owning PV and share it in the community or owning PV individually. As a result, using the same formula, two types of profitability were extracted: for cases where households share their PV with others or own PV systems individually.

Approaching the final step, the two types of profitability were visually compared to each other to get to the insights on how much more profitable PV sharing was over individually PV usage.

3. Results

This section presents the results as the average profitability and payback of all households participating in the 400 samples. In the following graphs, shared PV systems between 2, 5, 10, 20 and 50 households were, respectively, represented by the terms 2H, 5H, 10H, 20H and 50H. While individually owned systems were referred as 1H. All results were analysed in both Karlstad and Kiruna weathers.

The results first showed a short analysis of the electricity use profiles distribution in terms of annual electricity use. Afterwards, PV electricity supply in three different Swedish towns and electricity use of an average Swedish household combined with PV electricity supply. Later, profitability after 40 years and payback period were presented. In the graphs, the average household profitability was compared between the cases of individually owning a PV system and sharing PV systems with different number of households. The profitability was also analysed for four different PV systems sizes where the results were compared in two scenarios of electricity price growth rate: 2 % and 3 %. In the end, tax reduction was implemented for the cases with individually owned PV systems and compared to the cases without tax reduction.

3.1. Electricity use distribution

The annual electricity use from all 1067 apartments was calculated, presenting the following distribution: 10% of the apartments presented an annual electricity use lower than 1 000 kWh, 52% had annual electricity use between 1 000 kWh and 2 000 kWh, 25% presented values between 2 000 kWh and 3 000 kWh, 8% were between 3 000 kWh and 4 000 kWh and finally 4% presented values above 4 000 kWh.

3.2. PV supply

Figure 10 shows a SAM simulation for 1 kWp-PV system in Karlstad, Helsingborg, and Kiruna. As mentioned in section 2.2, the PV system configurations were azimuth of 180° and tilt of 20°. Even though, for Kiruna the optimal tilt would be different, the system was kept the same for all three locations to just observe the influence of the global irradiation in the electricity supply. As one can see, Karlstad annually supplies a similar amount electricity as in a southern Swedish city like Helsingborg. Meanwhile, in northern locations such as Kiruna, the same system supplies less electricity. The graph shows the considerable electricity supply difference between Karlstad and Kiruna, using PV of the same size. The analysis of PV supply allowed to choose the locations that will be focused on the current research, which are Karlstad and Kiruna.

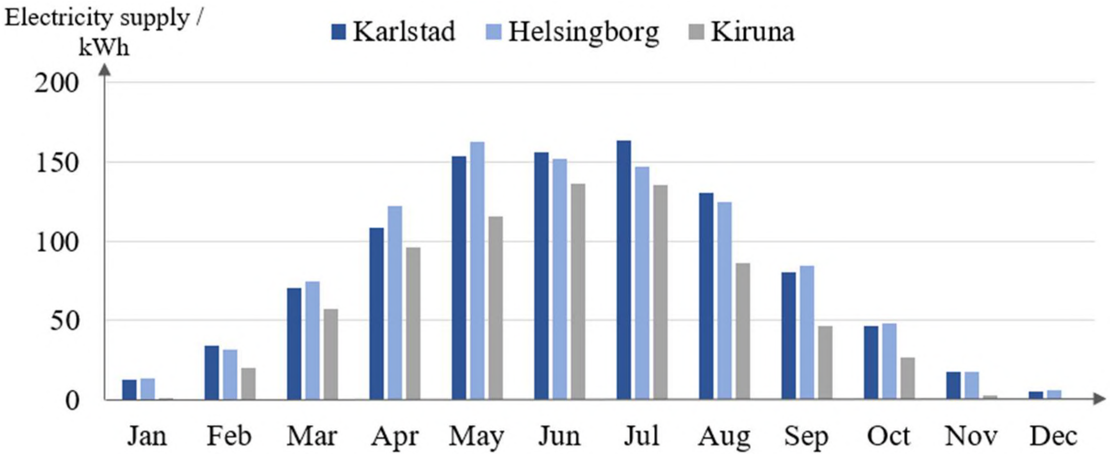

Figure 10 - SAM simulation: Monthly Electricity supplied by a 1kWp PV system in three Swedish cities: Karlstad, Helsingborg, and Kiruna.

3.3. Electricity balance

Figure 11 and Figure 12 below were created to visualise the correlation of two main components: PV supply of the previously mentioned 1 kWp system and electricity use of an average household in Sweden based on profiles from initial database. It was observed a mismatch between each other between the average electricity use profile and PV supply for Karlstad and Kiruna regions. This mismatch can be seen during the winter months, when the electricity demand is high but solar supply is low due to shorter days. It depicts well the typical situation in Sweden, where due to the geographical location, the self-use can be reduced by occurred imbalance of solar supply and electricity demand. The supply of the same PV size is larger in Karlstad than in Kiruna. However, when comparing two locations, it can be observed that the self-use of PV system in Kiruna is significantly larger than in Karlstad. It emphasizes the impact of correctly choosing a PV system can have on the amount of self-used electricity.

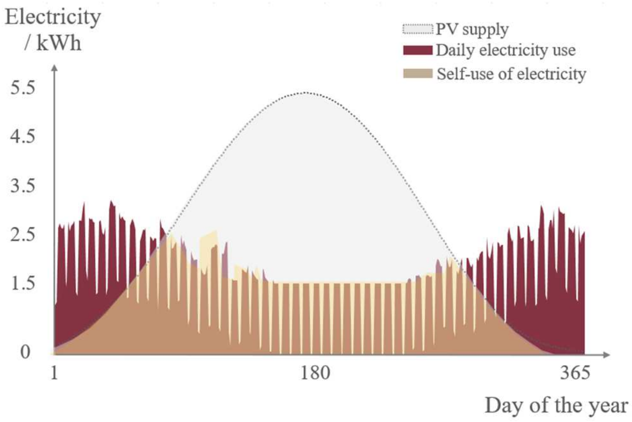

Figure 11 - Daily electricity use to PV supply graph for an average of 1067 studied profiles with PV electricity produced in Karlstad.

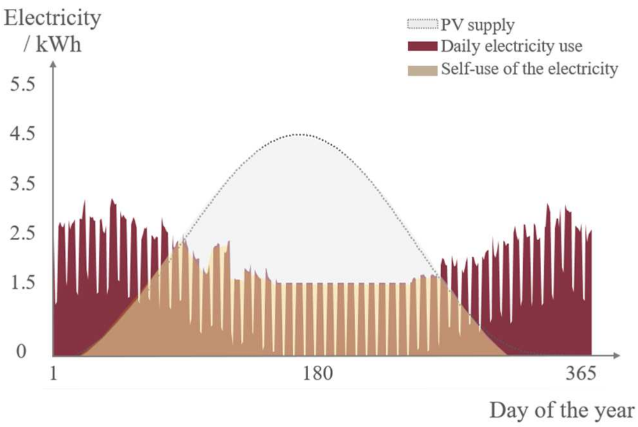

Figure 12 - Daily electricity use to PV supply graph for an average of 1067 studied profiles with PV electricity produced in Kiruna.

3.3.1. Sold electricity to the main grid

Figure 13 and Figure 14 show the monthly amount of electricity that a household sells to the main grid in different combination sizes using a 0.5 kWp system. Results showed that the amount of sold electricity decreases as combination size increases. The reason for that is in larger combinations, households trade more surplus electricity that is increasing their PV systems' self-use.

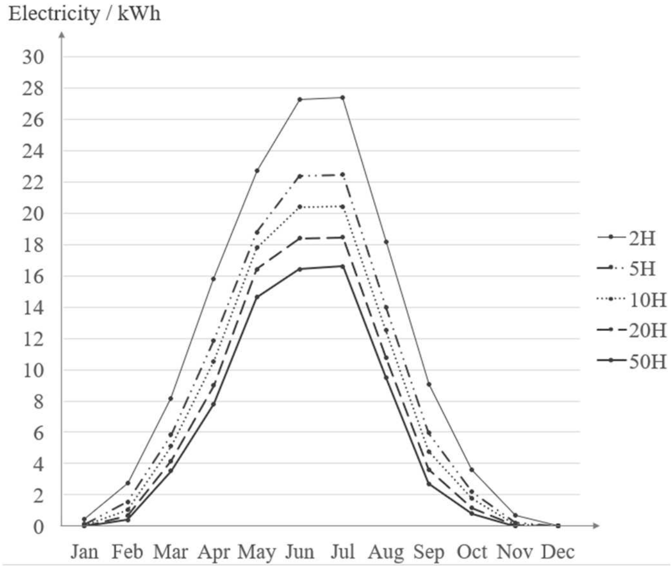

Figure 13 - Electricity sold to the main grid by an average household in different combinations (0.5 kWp). Karlstad.

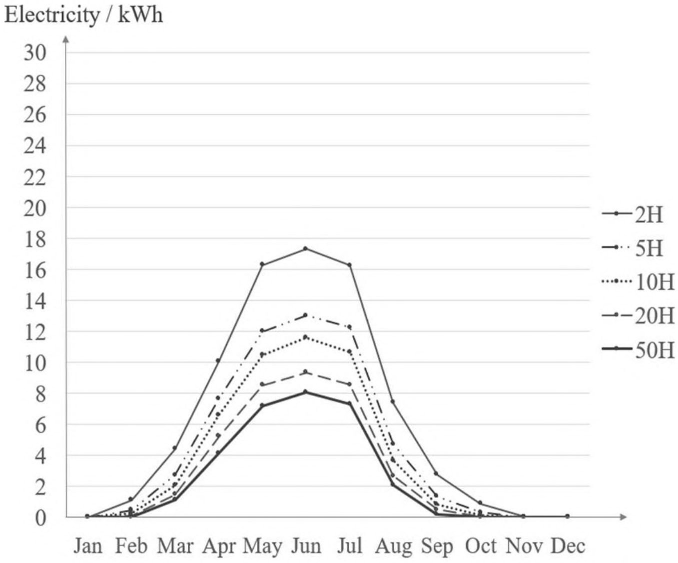

Figure 14 - Electricity sold to the main grid by an average household in different combinations (0.5 kWp). Kiruna.

In both Karlstad and Kiruna (Figure 13 and Figure 14), the behavior of curves in each combination correlate to monthly electricity supply in each location (Figure 10). In addition, it was observed that the difference between smaller combinations like 2H and 5H is greater than in larger groups. It is reasoned by increased synergy between the electricity use profiles due to their high variation.

3.4. Profitability and payback period

In this section profitability results were analysed over a period of 40 years. The results did not consider tax reduction incentive. Figure 15 and Figure 16 shows the average household profitability in the combinations of 1H, 2H, 5H, 10H, and 50H with a 0.25 kWp system per household. The results were displayed for the scenarios of electricity price growth of 2 % and 3 %.

Figure 15 showed the results in Karlstad. It was observed that a household sharing PV systems between 2 ,5, 10, 20 and 50 households presented a higher profitability when compared to a household with an individual PV system. For example, with an electricity price growth of 2 %, a household in combination 2H presented a profit of 1 610 SEK. It was an increase of 677 SEK when compared to the profit of 933 SEK for a household with an induvial system (1H). The average household profitability kept increasing as more households started share PV systems. However, the greater the number of households included in the combination, the smaller the increase in profitability. As one can see, a household in a fifty-household combination presented a small difference in profit (2 119 SEK) when compared to a household in a ten-household combination (2 071 SEK). Above all, the average household profitability increased in all combinations when electricity price growth change from 2 % to 3 %.

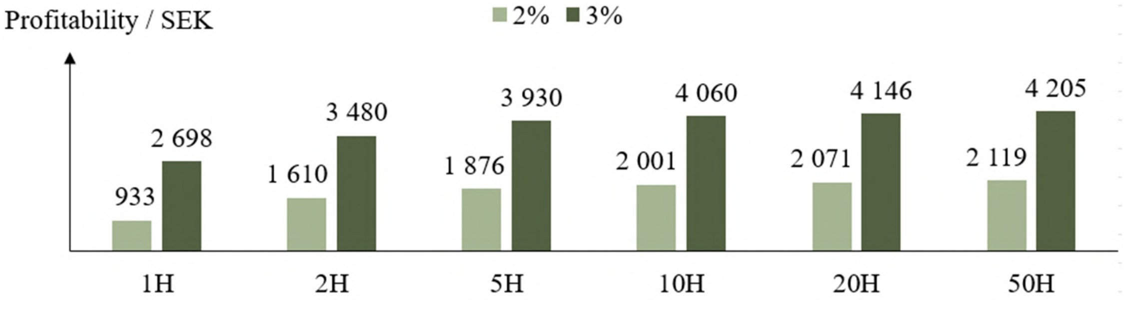

Figure 15 - Average household profitability with a 0.25 kWp PV system in Karlstad. Comparison between the electricity price growth scenarios of 2 % and 3 %.

Figure 16 showed the results in Kiruna. In none of the combinations, households have shown to be profitable with an electricity price growth of 2 %. Although, it was observed that the average loss decreased as more households were combined. For an electricity price growth of 3 %, an average household presented profit in all combinations, in which the average profitability increased when PV systems were shared within more households.

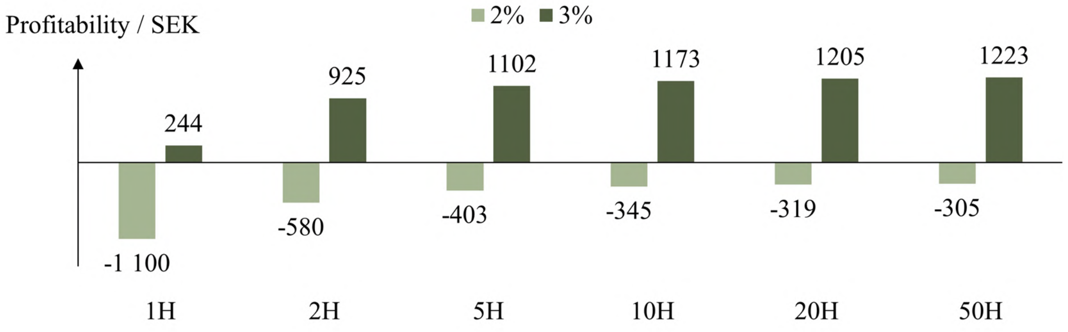

Figure 16 - Average household profitability with a 0.25 kWp PV system in Kiruna. Comparison between the electricity price growth scenarios of 2 % and 3 %.

Further, the average household profitability was presented in the same combinations but for different PV systems (0.25 kWp, 0.5 kWp, 0.75 kWp, and 1 kWp). Once more, the mentioned PV systems were used for each household, thus all households in each combinations had the same system size. With that in mind, Karlstad's results were displayed in Figure 17 and Figure 18.

Figure 17 presented the results for an electricity price growth of 2 %. The 0.25 kWp and 0.5 kWp systems kept profitable in all combinations. The 0.75 kWp system was only not profitable for one household with an individual system (1H) and the 1 kWp was not profitable in any combination. Moreover, one household with individual system (1H) and in a two-household combination (2H) had the 0.25 kWp system as the most profitable PV system. Whereas in combinations with more than two households, the 0.5 kWp systems presented the highest profitability. Meanwhile, when electricity price growth increased to 3 % (Figure 18), all four PV systems shown to be profitable in all combinations. Among all systems, the 0.75 kWp system was the most profitable. The second most profitable system was the 0.5 kWp followed by 1 kWp and 0.25 kWp.

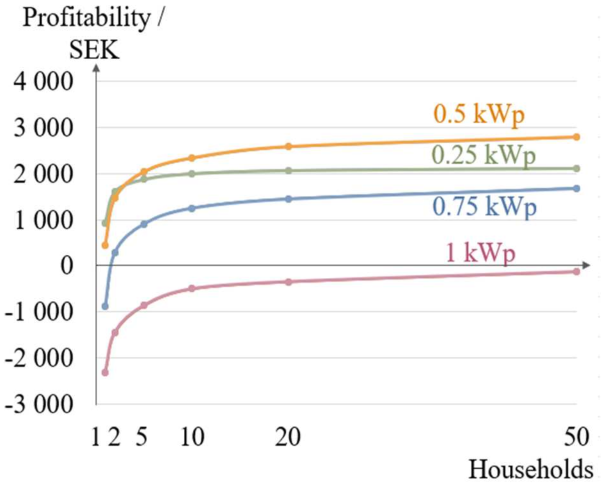

Figure 17 - Average household profitability in different combinations with different PV systems in Karlstad (Electricity price growth of 2 %).

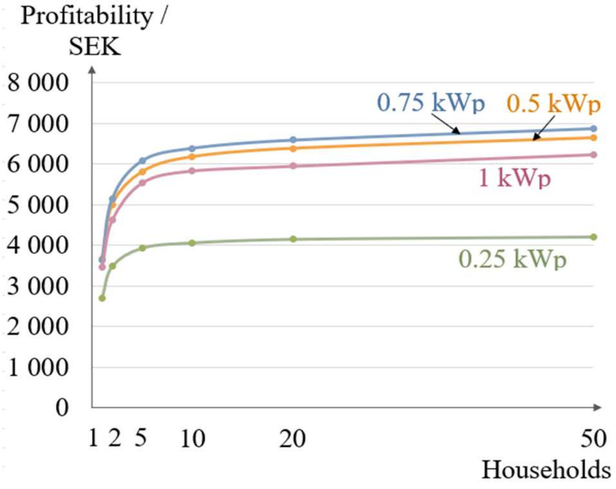

Figure 18 - Average household profitability in different combinations with different PV systems in Karlstad (Electricity price growth of 3 %).

Figure depicted the distribution of households per PV system, which drew an additional insight on why 0.5 kWp became more profitable than 0.25 kWp in larger combinations (5H, 10H, 20H, and 50H). In the graph, each bar represented the households in the 400 samples. The chart's X-axis displayed each analysed combination

(1H, 2H, 5H, 10H, 20H, and 50H). While the Y-axis displayed the share of households, in percentage, that had that respective PV system size being the most profitable one.

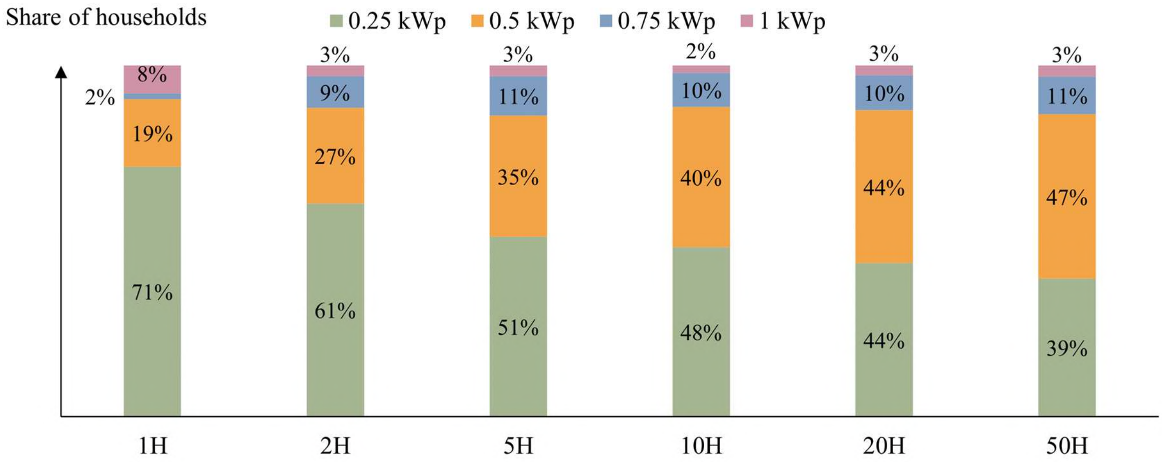

Figure 19 - Distribution of households in each combination regarding the most profitable PV system in Karlstad with an electricity price growth of 2 %.

For the 1H's samples, 71 % of the households had the 0.25 kWp system being their most profitable system. Whereas 19 % of the households had more profit with the 0.5 kWp system. For 2H, the percentage of households being more profitable with 0.25 kWp system was 61 %. Yet the percentage of households being more profitable with a 0.5 kWp system was 27 %. As combinations became larger (5H, 10H, 20H, and 50H) the percentage of households with the most profitable system being 0.5 kWp increased. While the percentage of households with the most profitable system being 0.25 kWp decreased.

Furthermore, Figure 20 and Figure 21 presented the average household profitability in Kiruna with different PV systems sizes. It was observed that none of the four PV systems were profitable when an electricity price growth of 2 % is considered (Figure 20). In that case, 0.25 kWp was the system size closest to be profitable. However, when the electricity price growth was 3 %, the average household profitability increased for all four systems (Figure 21). The 0.25 kWp became profitable in all combinations. The 0.5 kWp system only started to be profitable when household shared PV system (2H, 5H, 10H, 20H, and 50H). While the 0.75 kWp system showed to be profitable in combinations above five households. Still, the 1 kWp system was not profitable in any combination. Finally, a household in combinations 1H and 2H had the 0.25 kWp as the most profitable system. Whereas a household in the combinations 5H, 10H, 20H, and 50H 0.5 kWp demonstrated most profit.

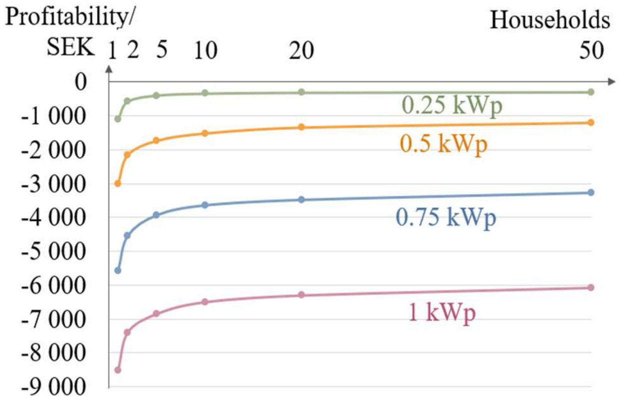

Figure 20 - Average household profitability in different combinations with different PV systems in Kiruna (Electricity price growth of 2 %).

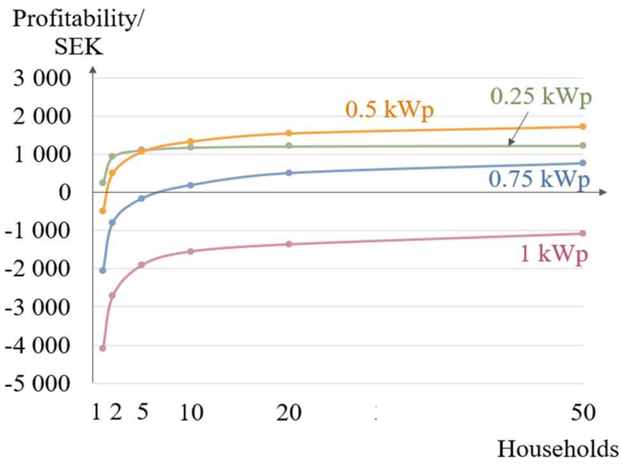

Figure 21 - Average household profitability in different combinations with different PV systems in Kiruna (Electricity price growth of 3 %).

Figure 22 presented the distribution of households per PV system size in samples simulated for Kiruna. It was noticed that in all combination the highest percentage of the households presented 0.25 kWp as the most profitable system size. When increasing the combination size this percentage slightly reduces reaching 83 % in fifty-households' combinations. Along with, the percentage of households having more profit with the 0.5 kWp and 0.75 kWp also increase to 13 % and 3 %, respectively.

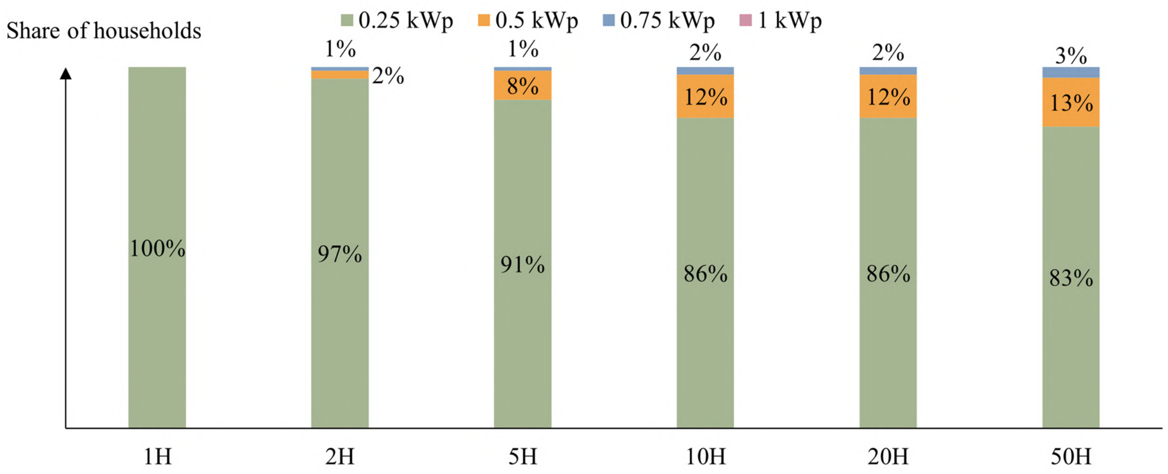

Figure 22 - Distribution of households in each combination regarding the most profitable PV system in Kiruna with an electricity price growth of 2 %.

When analysing payback, Figure 23 and Figure 24 showed the average household payback period for Karlstad with electricity prices growth of 2 % and 3 %, respectively. The payback time was represented by the year when the system becomes profitable for the first time. Both Figure 23 and Figure 24 showed a payback reduction for a household sharing a PV system. The shortest payback period was presented for a household with a 0.25 kWp system. The payback curves started to flatten after 5H combination, presenting the same payback period in combinations of 10H and 50H. One also can see, that for an electricity price growth of 2 % (Figure 23), the paybacks results were between 26 years and 45 years. However, when applied a higher electricity price growth of 3% (Figure 24), the results decreased to values between 20 years and 35 years.

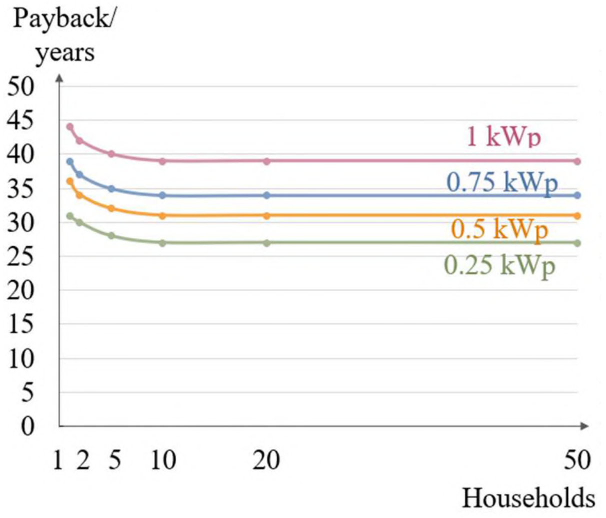

Figure 23 - Average payback time in different combinations with different PV systems in Karlstad (Electricity price growth of 2 %).

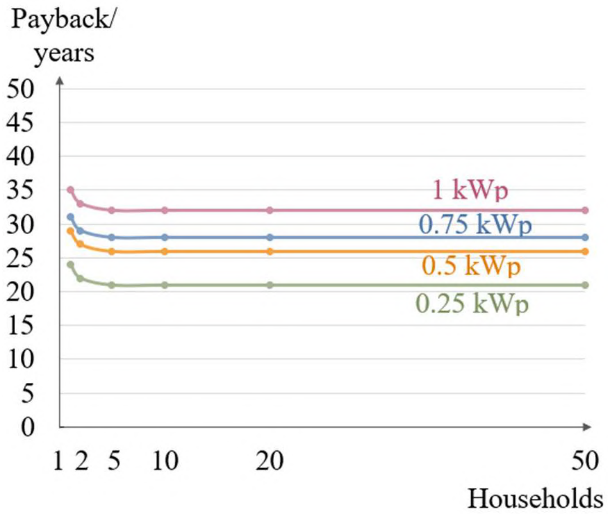

Figure 24 - Average payback time in different combinations with different PV systems in Karlstad (Electricity price growth of 3 %).

Figure 25 and Figure 26 presented the average payback period in Kiruna. It was noticed that the average payback periods reduced when the electricity price growth went from 2 % to 3 %. In particular, the 1 kWp system had its payback time reduced by 15 years when electricity price growth was increased. To repeat, the payback curves in Kiruna flatten as well, starting with 5H combination.

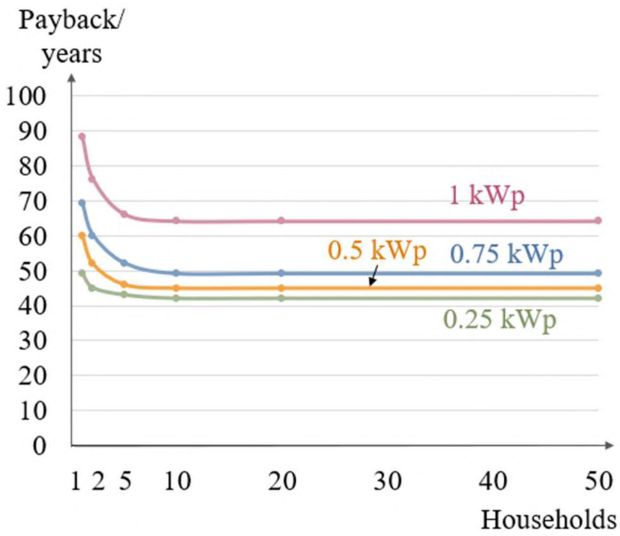

Figure 25 - Average payback time in different combinations with different PV systems in Kiruna (Electricity price growth of 2 %).

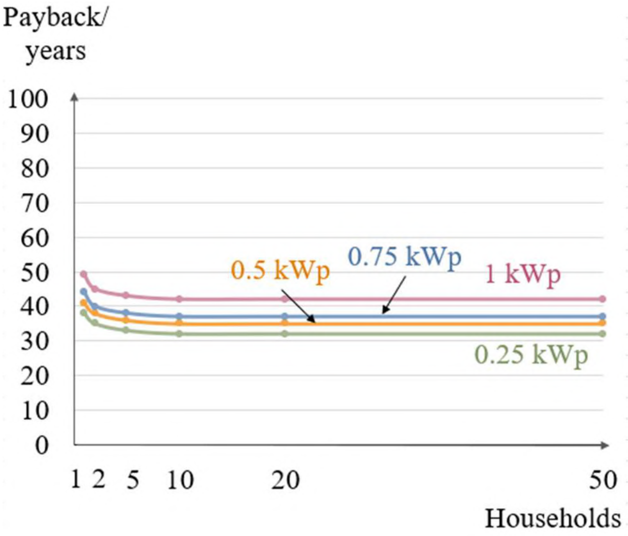

Figure 26 - Average payback time in different combinations with different PV systems in Kiruna (Electricity price growth of 3 %).

3.5. Sensitivity analysis: tax reduction

Furthermore, tax reduction was implemented for the cases with single households that own PV system.

Figure 27 shows the average profitability in Karlstad, where one household in a case with tax reduction was compared to another case without tax reduction. When considering the tax reduction benefit, one household (1H with tax reduction) presents a higher profitability with any system size when compared to other cases without tax reduction. The only exception was for a system of 0.25 kWp, where it showed to be more profitable when shared with other households. In terms of the most profitable system size, the highest profit of 6 200 SEK was presented for one household with a PV system of 1 kWp, considering tax reduction.

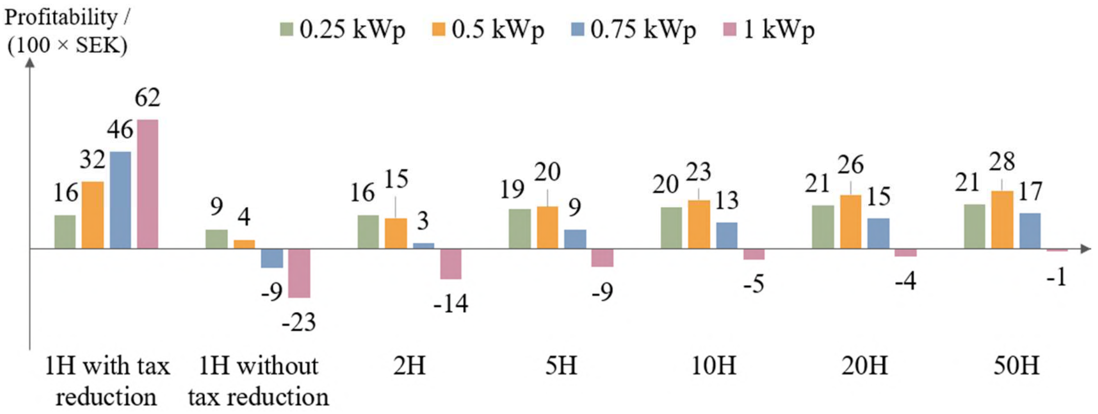

Figure 27 - Comparison of profitability of a single household receiving tax reduction to the shared PV communities without tax reduction in Karlstad with an electricity price growth of 2 %.

One can understand the contribution of the tax reduction in the profitability of single non-sharing household (1H) by observing Figure 28. By just selling electricity surplus, the average household profit for the system sizes of 0.25 kWp and 0.5 kWp were 900 SEK and 400 SEK, respectively. Meanwhile, for the system sizes of 0.75 kWp and 1 kWp, there was no profitability, indeed it presents losses of 900 SEK and 2 300 SEK, respectively. However, the average household tax reduction for the cases with 0.75 kWp and 1 kWp systems were 5 500 SEK and 8 500 SEK. It made those cases to be more profitable than the cases with 0.25 kWp and 0.5 kWp systems, that present a tax reduction of 700 SEK and 2 800 SEK, respectively.

Figure 28 - Impact of tax reduction on the profitability of a single household (1H).

In regard to the situation in Kiruna (Figure 29), it was observed that despite applying tax reduction to a single non-sharing household (1H), there was no profitability in any considered case. However, it was noted that with help of tax reduction the loss was significantly reduced among all PV sizes. As follows, the largest loss decrease from 8 500 SEK to 3 000 SEK was observed for non-sharing household with a 1 kWp system. Tax reduction affected the least households with a system of 0.25 kWp, where profitability was higher among most of the PV-sharing combinations (2H, 5H, 10H, 20H, and 50H). Resuming, with tax reduction applied, loss reduction was higher on cases with larger PV systems like 1 kWp and 0.75 kWp.

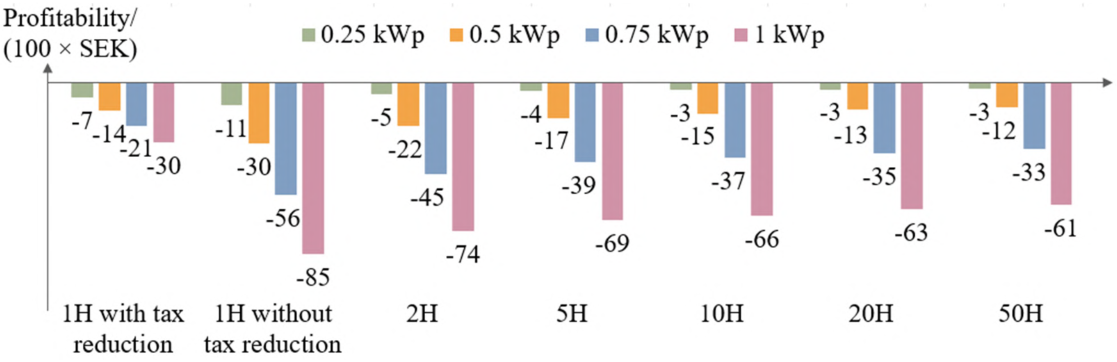

Figure 29 - Comparison of profitability of a single household receiving tax reduction to the PV sharing communities without tax reduction in Kiruna with an electricity price growth of 2 %.

The contribution of tax reduction for a single non-sharing household (1H) in Kiruna can be observed in Figure 30. For all cases, even though the tax reduction was applied, its total amount was insufficient to pay off the losses. As following, none of the cases became profitable. The largest loss decrease can be observed for a 0.75 kWp system where the amount was reduced from 5 600 SEK to 2 100 SEK and for 1 kWp system with a reduction from 8 500 SEK to 2 900 SEK.

Figure 30 - Impact of tax reduction on the profitability of a single household. Kiruna.

4. Discussion

The results of this study demonstrated that, in both Karlstad and Kiruna, shared PV systems were more profitable than individually owned PV systems. It was achieved because of electricity trading between households in residential communities. As previous research have demonstrated (Liu et al. 2018), prosumers can have more financial benefits trading electricity among themselves than trading with the electricity grid.

It is also seen that households, with individual PV systems, can increase their PV system size when sharing it with other houses to maximize their profit. The reason was found behind this is the increase of the system's electricity self-use by sharing it.
As mentioned by (Ramos et al. 2021), increase in self-use can be achieved with the use of shared PV systems. The analyses of sold electricity to the main grid in combinations of different sizes showed that by sharing the surplus electricity with more households, the amount of sold electricity to the main grid by an individual household reduces. It is explained by the increase of the self-use inside larger communities. In hours when electricity sharing happens, households that are in electricity shortage, use PV electricity surplus from other households. As follows, it results in cost savings for purchased electricity for individual households. The cost savings together with the sold electricity gains not only pays off the investment of larger systems but generates profit.

The payback analysis showed that a household can reduce the system's payback time by start sharing PV electricity with other households. This aligns with previous research (Reis et al. 2019) where it was portrayed the reduction in payback time when comparing sharing PV systems with individually owning one. According to (Palm 2018), the payback period can be one of the main barriers to prevent homeowners to invest in PV systems. Therefore, by reducing the system's payback, homeowners would be more willing to make decisions towards PV installation.

Furthermore, results showed that profitability curves flatten when they reach ten-households combination. It is explained by the variation of household's electricity use in the combination. Electricity trading is enhanced by combining households with different electricity use behaviour. Combinations with a larger number of households have more electricity being traded than smaller combinations. However, as combinations sizes increase the number of households with similar electricity use increases as well. It shows that household's electricity use variation in the combination has started to decrease. Thus, in smaller combinations, the average profitability presents high variation; however, the average profitability starts to normalize when increasing the combination size.

The results of this study showed that having profiles with different electricity use in the combinations enhances electricity trading in the community. Previous study (Fina, Auer, and Friedl 2019) determined the increase in profitability that prosumers can have when sharing electricity within a community of different buildings types. Depending on the building type, the electricity use varies due to different operational schedules, intensity use and size of the building. However, it is worth to note that the findings of the current study are applied only to electricity use profiles of residential buildings. Hence, if other building types were included in the study, it could lead to different profitability results. For the future studies, it is recommended to include other building types and study the effect of trading with mixed categories, e.g., industrial, commercial, and residential.

Moreover, a simple approach was used to create the electricity trading community. The approach was to consider the community as a group of households trading electricity directly with each other and the electricity grid. This would avoid fees or electricity taxes being applied to the electricity trading price. However, many previous research mentioned the necessity of third part, for example a company, to manage the electricity exchange among households and the grid (Liu et al. 2018). If so, some fee could be applied to the trading price. Hence, the price model would have to assure profitability to households trading electricity by setting the trading price amongst household to be higher the grid's selling price and lower than the grid's buying prices. Furthermore, future research can investigate the average household profitability using another pricing model or trading approach.

Another interesting finding was an impact of electricity growth rate on profitability increase. By slightly increasing electricity prices growth rate, it led to significant increase in profitability, and shorter payback time. It is mainly reasoned by the electricity running costs, considering sold electricity gains, on the life cycle costs.

Furthermore, the similar affect could be studied in the future based on the different price scenario. In this study 2019's prices were used; however, in price scenario of 2020-2021 that was not chosen for the main study, there was a notable difference in prices between northern and southern regions. According to the scenario, southern regions presented higher electricity prices for the north of Sweden. Thus, the profitability difference between two regions would potentially grow even bigger. It is also worth to note, that if distinct choices of electricity supplier would have been considered for analysis, the profit could have been different.

One of the findings that deserve additional attention is impact of tax reduction. Currently, subsidies implemented by the government in Sweden are a strong tool to motivate homeowners making decisions towards solar energy sources (Mundaca and Samahita 2019). Tax reduction helps to cover part of the system expenses and create awareness about value of PV systems. Even though, ROT deduction and tax reduction for Green Technology were excluded from this study. These subsidies currently allow to cover part of the expenses directly connected to installation or maintenance. As follows, if this subsidy package was included, the profit could have been slightly bigger than the one presented. Furthermore, in the case of sharing systems in a community, the investment and maintenance costs could be split between participants, that would reduce the expenses and shorten the payback period. The installation could also be simplified with shared PV systems, for example not all households would need individual inverters or mounted structures on the roofs. This would make installation planning simpler and would reduce the system cost. However, this was not considered in the study.

Moreover, there was no physical limitations, e.g. lack of roof space or shading from surroundings that had to be accounted for installation of PV panels in the current study. In terms of simplification, the same orientation, location of PV panels and roof tilt were applied to all cases. However, all mentioned variables can have a significant impact on PV production. Therefore, it is recommended that in the future studies each participative household would be approached individually, hence studies on variation of roof tilt and orientation, as well as location of panels would be performed to see how it affect the results of PV production.

Finally, in literature review, many discovered studies like (Reis et al. 2019) had been actively supporting an idea about using self-use as an indicator for evaluating potential profitability. However, one of the most important findings of this research showed that despite that self-use can help to predict the efficiency of the system, the financial part must be assessed before drawing conclusions about profitability. As the study showed, many variables like running costs of electricity, investment, subsidies, and maintenance costs can significantly influence outcome. Thus, their impact cannot be underestimated in the future studies.

5. Conclusion

The research was focused on analysing profitability while looking at multi-scaled communities with shared PV systems. The goal was to demonstrate, how profitable it was for an individual household to share PV systems community sizes and compare it to when they used the system on their own.

Overall, the study's findings confirmed that the individual profitability of a household was greater when PV systems were shared within a group of households, than when the PV system was owned individually. The outcome from the analysing in both locations, Karlstad and Kiruna, showed that no matter the system size or with how many households PV electricity was shared with, shared PV systems were always profitable.

Profitability increase was a result from the electricity trading between households, where a price model was implemented. The price model defined the trading prices among households as the average between the grid's buying prices and selling prices. This enabled electricity trading to be more financially advantageous than exchanging electricity with the grid.

Based on the results, the profitability of households increased when they share electricity in larger communities. However, there is initially a limited amount of surplus electricity the one individual household is able to give away to others, due to the need to cover their own electricity demand first. Nevertheless, the difference in profit between combination sizes eventually gets smaller. It was possible to confirm that depending on the case, after a certain combination size the profitability curve between communities eventually flattens, meaning that profitability stops to increase.

Furthermore, the study confirmed that by sharing electricity with more households the most profitable PV systems size increases. Though, it affected mostly smaller communities where the difference in profit is larger. If to share PV with large amount of households, the difference in profitability is minimal, hence the profit does not overcome the investment costs to own a bigger PV system.

Additionally, LCC analysis clearly stated that the impact of tax reduction cannot be underestimated. Based on the results of this study, it was concluded that tax reduction significantly increases the profitability of the bigger PV systems (0.75 kWp and 1 kWp). It was reasoned by the fact that with an increase of electricity production, more sold electricity can have tax reduction be applied to it. Nevertheless, the study showed that even without tax reduction, cases with smaller systems had higher profitability when shared. Despite all benefits of it, the results demonstrated that PV sharing can be beneficial on its own. Furthermore, since the subsidies are directly dependent on governmental goals, there are no guarantees it is still in place during the following years (Mundaca and Samahita 2019).

All in all, the current research demonstrated that even in countries like Sweden, especially in northern region, with less sunlight availability then southern European countries, the benefits of shared PV system are present. It is shown to be a great comparison to similar previous studies the had been developed in southern European countries.

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