Microproduction of Solar Electricity in Finland: Statistical Analysis

Master's thesis

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ABSTRACT

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The microproduction of solar photovoltaics (PV) has grown enormously in recent years in Finland, and it is expected to grow even further due to the ambitious renewable energy targets and the on-going smart energy transition. Nevertheless, there is a lack of country-level statistical analysis on the topic.

This thesis studies which sociodemographic, economic, and geographical factors explain the microproduction of solar electricity in Finland. The thesis consists of a literature review and statistical analysis on the electricity distribution system operator (DSO) level. The response variables are the number of prosumer contracts and the capacity of solar PV microproduction. The data, which were gathered from various open sources, is analyzed in a descriptive manner followed by multiple linear regression analysis. The analysis uses the ordinary least square method. In addition, profitability calculations are made to study economic incentives and barriers to the adoption of a PV system.

The results suggest that the microproduction of solar PV is connected to non-urban areas and higher mean age. Instead, there are not that many separate prosumers in urban areas, but single systems' capacities are more extensive there. The analysis showed that electricity price has a significant impact on the microproduction of solar PV. The profitability calculations support this result: electricity price substantially affects the viability of solar PV system investment. Thus, the introduction of financial incentives could enhance the adoption of solar PV systems among households.

This thesis offers a comprehensive overview of small-scale solar electricity production in Finland. However, the characteristics of the microproduction of solar PV are complex and involve various interactions that are difficult to capture in aggregated data. This offers an opportunity to repeat the analysis with a more detailed geospatial dataset in the future.

Keywords:	Solar PV, Microproduction, Prosumer, Decentralized energy production, Renewable energy, Multiple linear regression, OLS
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Aurinkosähkön pientuotannon määrä on kasvanut valtavasti viime vuosina ja kasvun oletetaan jatkuvan uusiutuvalle ja hajautetulle energiantuotannolle asetettujen tavoitteiden myötä. Tästä huolimatta, Suomessa ei ole tehty kattavaa tilastollista analyysia aurinkosähkön pientuotannosta ja siihen liittyvistä alueellisista tekijöistä.

Tässä työssä tutkitaan millaisia sosiodemografisia, asuinrakenteellisia ja maantieteellisiä muuttujia aurinkosähkön pientuotannon taustalla on. Tutkielmassa on myös laadittu kannattavuuslaskelmia kotitalouksien aurinkoenergiasysteemeille taloudellisten kannustimien tai esteiden selvittämiseksi. Aineisto on kerätty useista avoimista tietokannoista ja aggregoitu siirtoyhtiöalueille. Tutkittavina muuttujina ovat pientuotannon verkkopalvelusopimukset sekä aurinkoenergian pientuotantokapasiteetti. Metodina työssä on käytetty kuvailevaa analyysia ja usean muuttujan lineaarista regressioanalyysia, jossa on hyödynnetty pienimmän neliösumman menetelmää.

Tulosten mukaan aurinkosähkön pientuotannossa korostuvat maaseutumaiset alueet ja asukkaiden korkeampi keski-ikä, kun tarkastelussa olivat pientuotannon verkkopalvelusopimukset. Tutkimuksessa havaittiin, että kaupunkialueilla systeemikoot ovat suurempia, vaikka aurinkosähköä tuottavia kotitalouksia on vähemmän. Sähkön hinnalla huomattiin olevan positiivinen vaikutus pientuotannon sopimusten määriin. Tätä tulosta tukevat kannattavuuslaskelmat, joissa sähkön hinnalla oli selvä vaikutus aurinkopaneeleiden taloudelliseen kannattavuuteen. Taloudellisia kannustimia lisäämällä aurinkosähkön tuotanto voisi olla houkuttelevampaa kotitalouksille.

Tulokset antavat mielenkiintoisen kokonaiskuvan aurinkosähkön pientuotannosta Suomessa, mutta tarkempien sosiodemografisten ja asuinrakenteellisten taustatekijöiden identifioimiseksi analyysi tulisi toistaa alueellisesti tarkemmalla aineistolla, esimerkiksi postinumerotasolla.

Asiasanat:	Aurinkosähkö, Pientuotanto, Hajautettu energiantuotanto, Uusiutuva energia, Regressioanalyysi, PNS
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Contents

1 Introduction

Energy production is one of the biggest pollution sources: approximately 41% of all CO2 emissions originate from electricity and heat producers globally (IEA, 2020). Countries are now mitigating climate change by finding pathways from the fossil-based energy sector to emission-free energy production. One of those ambitious countries going through energy transition is Finland, which aims to achieve carbon-free energy production at the end of 2030 (Finnish Government, 2019).

Solar energy is one of the globally potential backstop technologies that uses a theoretically limitless energy resource, the sun. Photovoltaics (PV) are electronic devices that convert sunlight into electricity. The PV systems are easily scaled from small off-grid systems to large power plants. In between these two are on-grid microproduction, i.e. households, farms, and housing cooperatives that install PV systems to fulfill their energy usage and to sell the excess electricity to the grid.

The microproduction capacity of solar PV has grown massively in Finland: in 2016, it was 28 MW, and in 2019 the capacity was already 197 MW. A similar trend is visible in the number of prosumer contracts, that is, the contract that a household needs to both consume and produce grid-electricity. The number of prosumer contracts increased from 3900 to 23 500 between the years 2016 and 2019, the growth coming solely from increased microproduction of solar PV. Moreover, a recent study on Finnish attitudes on energy revealed that solar PV was the most accepted electricity source: 89% of the respondents wanted to increase solar electricity production in Finland (Finnish Energy, 2020).

In addition to clean energy production, microproduction of solar energy involves customers to become active participants in energy markets. Active participation will be even more critical in the future when customers will not just buy the electricity, but produce it and store it, for example, to electric cars. The change to the so-called smart energy system, that is, bi-directional power flow supported by computer and communications network (Lund et al., 2017), is just around the corner: Fingrid's electricity market's centralized information center Datahub is commissioned in 2022 (Fingrid, 2020).

Despite the growing interest and PV system installations, there is a lack of Finnish country-level statistical analysis of the residential microproduction of solar electricity, possibly due to the limited amount of empirical data this far. This thesis aims to contribute for this strand of literature by carrying out statistical analysis on the microproduction of solar PV. The approach is interesting, because it can utilize register data that has not yet been studied comprehensively. The findings may be interesting for policy-makers, energy companies and others that are interested in the factors behind small-scale solar PV production. In addition, to understand the context where prosumers act, the thesis also has an overview on policy framework, geographical potentiality, and PV system's installation and profitability.

The research question is which sociodemographic, economic and geographical factors are connected to the microproduction of solar PV in Finland. The question is approached by literature review and statistical analysis. The data for the analysis is gathered from open sources of Finnish Energy Authority (2020), Official Statistics of Finland (2020b) and European Commission PVGIS (2020b), followed by aggregating the data to electricity distribution system operator (DSO) level. The dependent variable is the number of prosumer contracts, explained by the variables describing area's sociodemographic characteristics, settlement structure, solar irradiation and electricity price. Also, capacity of microproduction of solar PV is analysed, but not as a main explanatory variable since it has less observations. The data is analysed first by a descriptive manner looking at correlations. This is followed by regression analysis using multiple regression model and OLS method.

The findings of the thesis indicate that prosumer contracts are connected to older age, lower income, and non-urban areas. Education and income showed moderate correlation with prosumer contracts, however, regression analysis did not find them having statistically significant impact on the prosumer contracts. The regression model was controlled by urbanity as it is assumed there are crucial omitted variables related to urban areas that thesis' data can not capture, such as availability of information and favorable culture. The marginal effects showed that the electricity price has a negative effect and age has a stronger positive effect on prosumer contracts in urban areas than rural areas.

On the contrary to prosumer contracts, PV capacity seemed to be differently related to the model variables: PV capacity is connected to urban areas, high income and education, and negative connection to electricity price. This difference between contracts and capacity can be explained by more extensive system sizes in urban areas, where, for example, malls and supermarkets take part in microproduction.

The limitations of roughly aggregated data sets restrictions for interpretation of the results. In other words, a lot of information on actual sociodemographic, settlement, and geographical factors are lost when the data tries to describe DSO areas that can cover almost half a million electricity distribution contracts. However, the thesis gives a comprehensive overview of the recent growth of microproduction of solar PV and leaves interesting research questions for the future.

The thesis is structured as follows: firstly, the previous literature is introduced. The second section focuses on the background of solar electricity production in Finland with the policy framework, the potentiality of solar PV, and economic viability calculations of residential solar PV systems. The fourth section provides data. The result of the descriptive analysis and regression are presented in section five. The sixth section discusses results, limitations and further research. Finally, conclusions are provided in the seventh section.

2 Literature Review

This section presents a review of most relevant literature for the thesis focusing on sociodemographic characters, economic factors and settlement structure of residential PV adoption.

The decision to adopt residential PV system has recently been studied from various perspectives. Some studies use empirically observed data from official registers for the analysis (e.g. De Groote et al. (2016); Kwan (2012); Schaffer and Brun (2015); Sommerfeld et al. (2017)) while most of studies utilize survey data and interviews to collect the information (e.g. Saikku et al. (2017); Schelly (2014); Oberst and Madlener (2014); Claudy et al. (2010); Leenheer et al. (2011)). In Finland, studies of Karjalainen and Ahvenniemi (2019), and Nygren et al. (2015) focus on interviewing forerunners and early adopters but there is a lack of country-level statistical analysis possibly due to limited amount of empirical data this far. However, Ruokamo et al. (2020) have recently studied the key drivers and barriers associated with household solar PV system adoption decisions under one of the largest DSOs in Finland, analyzing the data with multinomial logit model. Their study is based on a survey of households who already had adopted a PV system, in addition to randomly selected individuals without a PV system. Ruokamo et al. (2020) is referred a lot in this thesis because of its relatively similar research question and study location.

2.1 Sociodemographic Characteristics

In this section, I provide an overview on how sociodemographic characteristics of age, education and income are connected to residential solar PV production.

The literature shows evidence that the PV installations increase up to the retirement age. Younger people are more common in the consideration stage, being aware of environmental benefits but still not having the possibility to invest in a PV system (Balcome et al. (2013); Ruokamo et al. (2020). Again, older people have fewer intentions to self-produce electricity due to lack of knowledge, money, or feeling of certainty towards the new technology (Leenheer et al., 2011). This is supported by Kwan (2012), who finds that proportion of the population in either age class 25-34 or 55-64 have a smaller share of PV installations. This u-shaped correlation between age and PV adoption is logical since consumers age 35-45 have the greatest purchasing power compared to young adults or pensioners.

Education is ambiguously associated with the decision to install PV system. Dharsing (2017), Vasseur and Kemp (2015), and Balcome et al. (2013) find a significant positive relationship between education and the number of regional PV installations in Europe. Similar results are made in the US, where college or advanced degrees increase residential solar PV share by 2,8% in a zip-code level (Kwan, 2012). On the contrary, Sommerfeld et al. (2017) and De Groote et al. (2016) did not find education to be a significant factor in PV uptake.

Similarly, Ruokamo et al. (2020) found that high education decreases the probability of being an adopter of a residential PV system in Finland. Interestingly, the education level seemed to have a positive effect on being a considerer. This could imply that highly educated households would have interest in adopting solar PV systems but that they are facing some barriers for adoption. In a smaller sample interview-based study from Finland, on the contrary, the education level of interviewees was higher than in the population on average (Karjalainen and Ahvenniemi, 2019).

The financial situation seems to have an impact on adoption of solar PV system (Borenstein (2017), Kwan (2012), Dharsing (2017), Vasseur and Kemp (2015)). This is consistent as higher-income enables to overcome high upfront costs of PV systems. For example, Dharsing (2017) study in Germany shows evidence that even a feed-in-tariff does not equalize the adopters' financial background implying the high investment costs being a major barrier of adoption. In addition to income, Kwan (2012) finds economic factors of the cost of electricity and the value of the house significantly influencing the decision to adopt PV.

Likewise, in Finland, a financial barrier is overcome by a good financial position or by loaning money for investment (Karjalainen and Ahvenniemi, 2019). A more detailed description of the costs and profitability of PV system in Finland is represented in section 3.3.2.

However, there are contradicting results, as well. Sommerfeld et al. (2017) did not find a difference in the PV uptake share between the lowest income postal-code areas and others. They also find that people over 55 years are more likely to have PV, which might explain this result of low income: pensioners may not have high monthly income flow but they own property and dwellings, making them wealthy. Also, Ruokamo et al. (2020) did not find a statistically significant connection between income and PV adoption, however, the connection between income and non-adoption was negative and significant implying that non-adopters have lower income compared to PV adopters.

This review on sociodemographic characteristics has shown that age has a positive connection to PV system adoption up to retirement age. Socioeconomic status, that is, education and financial position, have more ambiguous connection to microproduciton of solar PV. Usually, higher income and education implies greater likelihood of installing microgeneration, even though contradicting results exists, as well.

2.2 Settlement structure and geographical factors

This section looks at what kind of building types, settlement density and geographical characteristics are connected to microproduction of solar PV in the previous literature.

Most prosumers live in their own single-family house, and PV systems in apartments for individuals are rare (Vasseur and Kemp, 2015; Balcome et al., 2013; Schaffer and Brun, 2015). In addition to homeownership, house size impacts the decision to adopt PV (Balcome et al., 2013; Ruokamo et al., 2020). Larger houses' energy consumption is higher, and thus self-production of electricity is sensible.

There is no consensus about the relationship between residential PV installations and building density between countries. Living in the countryside or small village increases the likelihood to have a PV system in a recent study from Finland (Ruokamo et al., 2020). In the Netherlands, most of the prosumers live in town instead of cities or the countryside (Vasseur and Kemp, 2015). Dharsing (2017) does not find a clear relationship between settlement structure and PV adoption in Germany, but on the contrary, Schaffer and Brun (2015) find house density as a decisive factor. In the US, suburban areas are found to be negatively associated with residential solar PV installations (Kwan, 2012). Kwan (2012) suggests this phenomenon be related to the factors of income level and political orientation that is linked to the decision to adopt PV.

Installing PV systems in an apartment building for residential use has not been possible until now in Finland. Thus, there are no studies concerning the housing type yet. However, a survey revealed that people have a positive attitude towards residential renewable energy production in the capital area of Finland. Most of the semi-detached and single-family house households show interest in utilizing the backyard or roof space for renewable energy technology, such as PV. (Jung et al., 2016).

The literature shows significant spatial spillovers, that is, PV installations are clustered in specific locations (Dharsing, 2017; Schaffer and Brun, 2015). Also, Kwan (2012) identifies the clustering effect in his study on the US: neighboring zip codes have similar residential PV share. This might be explained by similar sociodemographic factors or by the knowledge and example that neighbors set to each other. The lack of information is a major barrier to adopt PV (Nygren et al., 2015; Hai, 2019), and maybe in certain areas, the level of information and empirical experience are higher, making PV electricity more popular. Similar "peer-effect" comes up in Ruokamo et al. (2020): a person is more likely to adopt a solar PV system if the person knows someone who has already done so.

The efficiency of PV cells increases with solar radiation. Thus it is logical that the number of irradiation influences the density of PV installations (Kwan, 2012; Dharsing, 2017). For example, Schaffer and Brun (2015) have found solar radiation to have a significant positive influence on an area's PV uptake - this means that in Germany, most of the residential PV installations are located in the Southern parts of the country.

To summarize, microproduction of solar PV is connected to owner-occupied and relatively large dwellings. There is no consensus if the installations are concentrated to rural, urban or suburban areas, however, cluster-effect is common. Also, solar irradiation affects the PV system uptake.

2.3 Motivations for microproduction

Next, the most important motivations for adopting a solar PV system are identified in the light of previous studies.

The impact of environmental attitude is considered significant especially in the studies relying on interviews and surveys. Ruokamo et al. (2020) show that PV system adopters are likely to take environmental aspects into account when doing the investment decision. Karjalainen and Ahvenniemi (2019) and Nygren et al. (2015) both studied early adopters of PV systems in Finland and also conclude environmental reasons and production of pollution-free electricity to be the most common motivation for adopting PV systems. This is in line with results from other countries, for example, Balcome et al. (2013) state that environmental benefits are a significant motivation to install a PV system in the UK.

However, PV systems are still relatively new technology and the interview studies have focused on early adopters that do not represent the majority of existing and potential PV adopters. According to Rogers (1995), early adopters are generally keen on e.g. technology or environment whereas the majority of adopters of the technology avoid financial risks and wait until adequate experience is collected.

Other major motives for adopting solar PV are affinity with technology and security of electricity supply. Leenheer et al. (2011) conclude in their interview-based study that, after environmental concern, affinity with energy and technology is the most important driver for generating their own energy. Similarly, Schelly (2014) reports that the adopters most often share an interest in the electricity generation and usage in the US. These adopters pay attention to households' energy usage and state to have more knowledge of technology than an average person. This group perceives PV production as a hobby, as stated by Karjalainen and Ahvenniemi (2019), who also add that usually it is pursued as a hobby more often by a male than a female.

Furthermore, self-sufficiency is an important reason to adopt PV (Saikku et al., 2017; Schelly, 2014; Oberst and Madlener, 2014). Nygren et al. (2015) mentions that interviewees expected electricity prices to rise, which encourages them to self-produce electricity. In addition, households in remote locations may suffer from power cuts and thus at least partial self-sufficiency in electricity may bring security and even monetary benefits (Karjalainen and Ahvenniemi, 2019).

To conclude, most commonly mentioned motivation for residential solar PV production in the literature is environmental benefits. In addition, self-sufficiency and interest in technology are often identified as motivation.

3 Solar power in Finland

Solar power plays still a minor role in the entirety of energy production in Finland: in 2019 it was 0,003% of electricity production. However, solar was the fastest-growing energy source by doubling its electricity production between 2018 and 2019. The biggest electricity sources are nuclear power (35%) and combined heat and power production such as district heat (33%). The share of hydro-power is 19% and wind power 9% of electricity production. Domestic energy production is supplemented with imported electricity that was 23% of electricity production in 2019. (Official Statistics of Finland).

To understand better the context of the thesis, this section gives a short overview of the political framework, potentiality, and economic situation concerning the microproduction of solar PV in Finland.

3.1 Policy framework

The energy sector released 38,8 million tons of CO2 equivalents into the atmosphere in 2019, constituting 74% of Finland's total greenhouse gas emissions that year (Official Statistics of Finland, 2020c). Therefore, it is natural that many ambitious emission reduction goals are set for the energy sector, on top of the emission reductions imposed by European Union emission trading system (EU ETS). The governmental program of Finland states that the energy production will be emission-free at the end of 2030 (Finnish Government, 2019).

Figure 1 visualizes Finland's energy sector projection until year 2040. The projection is based on the climate policies presented in the Energy and Climate Strategy and the Medium-term Climate Change Policy Plan in addition to some additional climate- and energy policy measures implemented after the year 2018 (Ministry of Economic Affairs and Employment, 2019). The projection shows that Wind power and PV are expected to increase their share of electricity production significantly until the year 2030. The share of solar electricity is expected to grow from the current 0,2 TWh to 1.1 TWh of gross final consumption in 2030 (Ministry of Economic Affairs and Employment, 2019).

Despite ambitious goals, there are no binding national targets for solar power. However, the aim is to increase the share of solar and wind power, and the total use of renewable sources of electricity will be increased significantly (Finnish Government, 2019). The decision of ending charcoal use in 2029 will create more markets for renewable energy sources. In addition, the government program targets a stepwise phase-out of the use of oil for heating by the beginning of the 2030s and a halving of the use of peat in energy production by 2030 (Finnish Government, 2019).

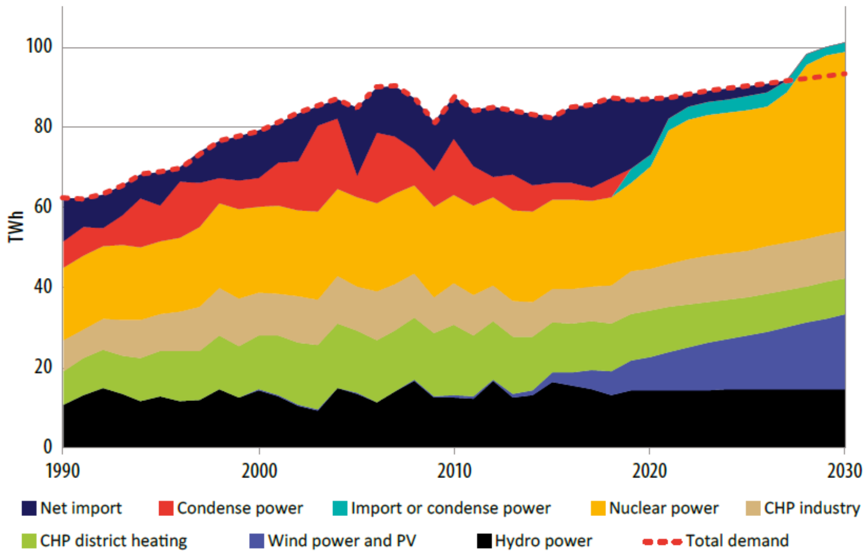

Figure 1: Development of electricity demand and supply in the WAM (with additional measures) projection

Source: Ministry of Economic Affairs and Employment (2019)
Note: The projection is based on the energy and climate strategy and the medium term climate policy plan specified in the 2015 government program. The projection includes also additional measurer (WAM measures) that are implemented after 1.1.2018

When it comes to small-scale production, Finland relies heavily on market-based development. The technology is developing and thus becoming cheaper and additional monetary subsidies are not considered necessary. Instead, the government underlines the development of markets to the direction where customers can have an active role (Finnish Government, 2019). Advanced storing systems and demand responses optimize the electricity consumption but also makes own energy production more feasible.

Some changes in legislation and taxation are taking place to incite microproduction: industry tax refund for heavy electricity users will be removed but the electricity tax for industries will be decreased to the minimum level. Also, double taxation of storage of electricity will be removed. (Finnish Government, 2019).

Another important change is that housing cooperatives will have the possibility to form energy communities that can act as a small-scale energy producer utilizing their production similarly as e.g. detached houses already do. Also, regulation on net-metering will be unified, which previously lead to unequal treatment of prosumers under different DSOs. These renewed regulations came into force 1.1.2021 and will be deployed in every DSO at latest in 2023. (Lähienergia, 2020).

3.2 Potentiality of solar energy in Finland

This section examines what are the opportunities for utilizing solar PV in Finland in the light of geographical location.

The total theoretical capacity of residential solar PV in Finland is estimated to be 3,5GW (European Commission, 2017). For comparison, on-grid and off-grid PV power production were 0,1335GW in Finland in 2018 (Ahonen and Ahola, 2017). The potential capacity number is derived from the area of suitable residential rooftop area for PV production and the assumption that 0,13kW solar PV would be installed per $1m^2$ of suitable roof space. The biggest theoretical capacity potential in EU is in France (37,6 GW) and the UK (37,7 GW). (European Commission, 2017).

In Finland, in addition to the suitable roof area, the major restrictive factor of the potential capacity of PV power is limited irradiation due to Nordic circumstances. In southern Finland the irradiation reaches the same level as in, for example, Germany, the yearly sum of global irradiation being over 1100 kWh/m^2 and the yearly sum of electricity generated by 1 kWp system being over 850 kWh/kWpeak for optimally inclined

Figure 2: Global irradiation in Finland

Notes: The colors represent yearly sum of global irradiation (kWh/m^2) (values at the top of the bar) and yearly sum of solar electricity generated by 1kWp system with performance ration 0.75 (kWh/kWp) (values below the bar)
Source: European Commission PVGIS (2020a)

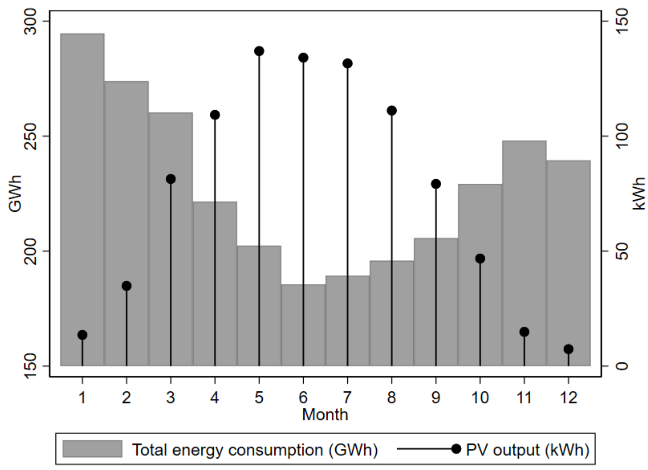

Figure 3: Average monthly energy output of PV modules in Turku and total electricity consumption in Finland

Notes: Monthly household level data on electricity consumption not available, thus total consumption of Finland used.
Source: European Commission PVGIS (2020b) and Nord Pool (2020)

PV modules. The least potential is in Northern Finland, where the yearly sum of global irradiation is $900kWh/m^2$ and electricity generated is 675 kWh/kWpeak. (European Commission PVGIS, 2020a). The global irradiation and solar electricity potential for optimally inclined PV modules in Finland are illustrated in figure 2.

Another important aspect is the seasonal changes of solar irradiation. The PV modules do not produce a stable amount of electricity all year round in Finland. Figure 3.2 shows the average monthly energy output from optimally inclined PV modules in Turku, Finland. The energy output is extremely low in the winter months and the production potential is focused from March to September. The variation is even higher in more northern locations - Turku is one of the most southern cities in Finland. Figure 3.2 also illustrates the mismatch of electricity consumption and PV electricity production. The consumption peak is in the wintertime, whereas in summer, consumption of electricity is relatively low.

In addition to solar irradiation, other climatic conditions affect the power generation of the PV system. A high air temperature can reduce the PV panel output from 2% to 22% (Kazem and Chaichan, 2016). This fact improves Finland's potential PV electricity production because the solar panel's back temperature stays cool in the Nordic climate. Other factors affecting the power generation of PV system are air humidity and wind speed: increased air humidity declines the panel output power whereas wind improves it by a cooling effect (Kazem and Chaichan, 2016).

3.3 Production and selling

This section provides information on adoption of PV system comprehensively. In order to understand the variables related to prosumers, it is crucial to understand what is required to become a one. Thus, I will shortly address the practicalities that the prosumer needs to take into account in the investment-decision. This is followed by profitability calculations for residential PV system to get realistic information on financial viability of the investment.

3.3.1 Installation of PV system

The PV system consists roughly of two parts: panels and an inverter. The panels are usually made from silicon cells that convert solar radiation into electricity. The system does not necessarily need direct sunlight because the cells can utilize global irradiation. Efficiency rate denotes the efficiency to convert solar irradiation into electricity. Currently, a standard commercial solar cell has an efficiency rate of 15-17% (Motiva, 2020). The efficiency rate is expected to increase in the coming year as a result of improving technology, bringing new types of technologies, such as thin-film modules, reachable for small-scale producers (Ahonen and Ahola, 2017).

The inverter is needed to convert the direct current power to alternative current power that is used in grid electricity. The producer also needs a feed-in electricity meter, that reports the amount of power produced, and a consumption meter reporting the electricity usage. (Motiva, 2020).

Before installing the PV system, a producer needs to take various things into account. First, the producer must notice the restrictions and regulations that vary between municipalities. In Finland, some municipalities require construction permits but usually, just notification from the producer is enough when it comes to small-scale production. (Energiateollisuus, 2019).

Next, the producer needs to make a contract with the local electricity distribution operator (DSO). DSOs are responsible for operating and maintaining the distribution grid in their operating area. The DSOs are regulated local monopolies and consumers cannot change the distribution service provider. Some DSOs can charge a fee, at most 0,07c/kWh, for feeding the excess electricity into the grid (Motiva, 2020).

As with many other renewable energy sources, PV is not a stable energy source and it rarely equals the electricity consumption of the unit it is built for. Thus, the prosumer should have another source for electricity, in addition to PV. The most common solution is to make a contract with an electric company to buy additional energy and sell excess electricity if needed.

The electric retailers have different contract types with varying purchase price. Therefore, for the prosumer it is worth tendering out the electric retailers. In general, the producers receive the Nord Pool Spot price of the excess electricity they sell (Motiva, 2020). The price is usually the same for buying electricity. However, when buying the electricity from the grid, taxes and distribution fees, and potential sales margins are charged in addition to the spot price making the selling price notably smaller than the buying price (Motiva, 2020). In Finland, the taxes and distribution fees can be over half of the electricity price. Thus, it is most feasible to utilize the electricity produced by the PV system as efficiently as possible.

The alternative to selling of excess electricity to the grid is to have a storage system for excess energy. According to the literature, using domestic heating water for energy storage can offer significant energy cost savings and flexibility to the energy use (Cao et al., 2013; Salpakari and Lund, 2015). Recently, Huuki et al. (2020) found that hot water heating optimization based on hourly prices and own solar power production is more beneficial than the time-of-use optimization strategy. Excess energy can also be stored in lead-acid batteries and more efficient lithium batteries. However, the prices of storage systems based on modern lithium-technique are still too high for the widespread commercial use of small-scale producers. In the future different kind of storage system that, for example, Tesla, Sonnen Batteria, and Varta Element offers, will potentially be a global trend in PV systems (Ahonen and Ahola, 2017). Batteries enable self-sufficient use of electricity and are also an important part of the smart energy transition, where customers are expected to have an active role as a part of the demand respond.

3.3.2 Prices and Profitability

The PV system's profitability is commonly evaluated by net present value (NPV), internal rate of return (IRR) and the payback time of the investment. To understand how viable the PV system investment in Finland is, I have calculated the most common economic statistics for the PV system in six different locations in Finland. However, the results are difficult to generalize because the PV technology and the electricity markets are developing fast, making profitability estimates outdated quickly. Also, the calculations include various assumptions that need to be evaluated case-by-case in the real viability estimation for a household's PV system investment.

The solar PV system is sized according to the electricity consumption. In these calculations, a household without electric heating means a small dwelling with yearly electricity usage of 5000 kWh. A house with electric heating representing a bigger dwelling with annual electricity consumption of 18 000 kWh. The correct sizing of a solar system is essential because it is economically viable to cover the most energy use yet without oversizing the PV-array. Many solar system companies advise sizing the system to cover 30-40% of the yearly electricity consumption. This is realistic since the mismatch of sun irradiation and consumption peaks are not simultaneous (see figure 3.2). A higher cover of annual electricity consumption would be hard without producing an inefficient amount of excess electricity.

By following this rule, households without electric heating should buy a solar PV system that would produce approximately 2000 kWh per year. This electricity production level can be reached by choosing a system size of 2,7 kWp, which produces 2024 kWh per year in Espoo, assuming that the PV system's efficiency rate is 13%. Similarly, for a house with electric heating the optimal solar PV system size is 5,5 kWp.

The costs for the PV system are set based on current offers of PV system retailers in October 2020. For a smaller system size of 2,7kWp the investment costs are assumed to be 6000€. Similarly, the prices for the bigger system size of 5,5 kWp is approximately 7500€. (Aurinkosähköäkotiin.fi, 2020). However, the calculations take household tax refunds into account, approximately 900€ for the PV system installation.

The PV system will produce excess electricity even though the system size would be optimized. Huuki et al. (2020) estimated that a household sells 7-47% of the solar electricity to the grid depending on the system's location, sizing and electricity-use optimization strategy. They also assumed that the household has a hot water heating system to store and utilize solar electricity. I will assume that the excess electricity fed to the grid is 25% in Espoo and Turku, 20% in Jyväskylä, Joensuu and Oulu, and 15% in Rovaniemi, based on Huuki et al. (2020) estimations.

It is assumed that PV system lifetime is 30 years and that the inverter needs to be changed once. The cost of changing the inverter is 8% of the investment costs (Motiva, 2020). It is also assumed that there will be some maintenance costs, approximately 100€ per year.

The location of the system affects the irradiation level and, thus, the system energy output. I focus on Espoo, Turku, Jyväskylä, Joensuu, Oulu and Rovaniemi to see if

Table 1: 5.5 kWp PV system's profitability statistics in six different locations

Location	Turku	Espoo	Jyväskylä	Joensuu	Oulu	Rovaniemi
Irradiation kWh/m^2/y	1284	1222	1071	1063	1111	979
NPV €	1 065€	-398€	-312€	-86€	79€	-537€
IRR %	4.18%	2.53%	2.62%	2.90%	3.09%	2.37%
Payback time (years)	21	25	26	25	24	26

Notes: This table presents profitability calculation for PV installations in different locations. 5.5 kWp system is sized for a house with electric heating (consumption 18 000 kWh/year)
Source: Own calculations.

Table 2: 2.7 kWp PV system's profitability statistics in six different locations

Location	Turku	Espoo	Jyväskylä	Joensuu	Oulu	Rovaniemi
Irradiation kWh/m^2/y	1284	1222	1070	1063	1111	979
NPV €	468€	-733€	-669€	-476€	-341€	-845€
IRR %	3.55%	2.10%	2.18%	2.42%	2.59%	1.96%
Payback time (years)	25	>30	>30	>30	>30	>30

Notes: This table presents profitability calculation for PV installations in different locations. 2.7 kWp system is sized for a house without electric heating (consumption 5000 kWh/year)
Source: Own calculations.

the irradiation level affects the profitability of PV investment. These locations represent different geographic sites in terms of longitude and latitude. The irradiation levels are from European Commission (2017). The economic characteristics of a bigger system (5.5 kWp) in each location are presented in table 1. Similarly, for a smaller system (2,7 kWp), the characters are in table 2. To see the more detailed calculations, see appendix A.

The NPV of the investment is the sum of the discounted stream of yearly savings from using the solar electricity R_t:

$$NPV = \sum_{t=1}^{T} \frac{R_t}{(1+r)^t}$$

Where $T = 30$ years and interest rate $r = 3\%$ that is the same used in the study of Huuki et al. (2020). The internal rate of return IRR can be compared to the other investment possibilities of a household. The IRR tells the required rate of return to reach viable net present value for investment:

$$\sum_{t=1}^{T} \frac{R_t}{(1+r)^t} = I$$

Where R_t is yearly savings from using the solar electricity and I is the investment costs.

A positive NPV is commonly regarded as a good investment. Looking at the tables 1, 2 and figure 3.3.2 it can be seen that the only economically viable PV system investment with both system sizes and prevailing assumptions is located in Turku. Prosumers can expect a relatively good internal rate of return in this area: 4.18% for the bigger system and 3.55% for the smaller system. The bigger system is also viable in Oulu's irradiation level, the NPV being just above zero and IRR 3.99%.

Instead, Espoo, Jyväskylä, Joensuu and Rovaniemi are not considered as a suitable location in the name of economic viability. This implies that the irradiation level has a significant impact on the calculations. It looks like coastal areas are more suitable regions,

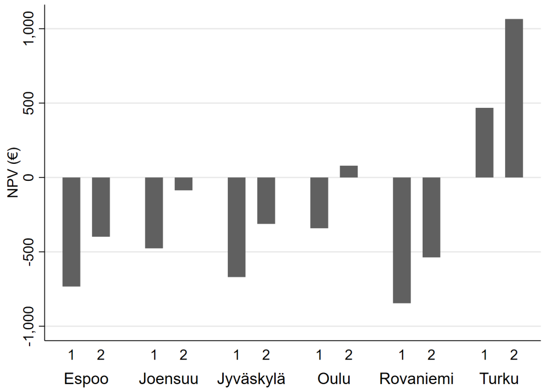

Figure 4: Net present value of PV systems in six different locations in Finland

Note: The figure shows NPV for PV system size 1 that is 5.5 kWp (for a house without electric heating) and 2 that is 2.7 kWp (for a house without electric heating).

Oulu and Turku both being in the coast, even though Oulu is the second most northern city in our calculations. The northernmost location is Rovaniemi, located just in the arctic circle, where PV system would be viable with IRR of 2.37% (bigger system) or 1.96% (smaller system).

The issue in northern locations is the inability to utilize the electricity on-site and avoid selling the electricity to the grid with a low price. This is because the solar irradiation is not matching the consumption. In summer, a large share of generated energy is sold to the grid and in the winter, when the electricity demand is highest, the sun is not shining for months. The mismatch between electricity consumption and solar generation can be a key barrier for low self-utilization level and the feasibility of the system (Huuki et al., 2020).

The mismatch issue could be reduced by storing the excess energy to be used later. Huuki et al. (2020) argue that the optimization of hot water heater electricity consumption in response to the household's solar power generation increases the profitability of PV investment. More recently, Huuki et al. (2020) found that optimizing the hot water heating with solar electricity can increase the IRR by 0.6%. The lithium-based storage systems will most likely have an essential role in the PV systems in the future when the prices of the technology are affordable for small scale producers (Ahonen and Ahola, 2017). New technologies are also arising. For example, Heliostorage has developed a technology that stores the solar energy below the ground and is used in the winter with a basic heat pump (Heliostorage, 2020).

In addition to the irradiation level, the size of the system impacts profitability. The PV system prices stay relatively similar, even though the size of the system changes. For example, I use a market price of 6000€ to PV system sized 2,7kWp and 7500€ to 5,5kWp system – the price difference is only 1500€ even though the bigger system is double as a capacity. The investment is still viable in Turku for the smaller system, as the table 2 shows. However, the most significant changes are in payback time compared to the more extensive system. The investment has paid itself back in 25 years in Turku, but in other locations, the payback time is over 30 years that is the estimated lifetime for a PV system.

Moreover, the price of electricity affects viability. I looked at economic characteristics, both with the highest (4.18 cent/kWh) and lowest (1.48 cent/kWh) electricity distribution price in 2019. This calculation is shown in the appendix. When the electricity distribution price is high, system size is 5.5 kWp and location Espoo, the payback time decreases to 20 years, NPV is 1 464€, and IRR is 4.61%. Instead, when looking at the lowest distribution price, replacing the grid electricity with PV electricity is not profitable. Payback time is 25 years, NPV is -1 092€ and IRR is 1.68%. Therefore, the PV system's opportunity costs, that is, the electricity price, significantly affect economic characteristics.

However, traditional decision-making tools may not be the best tools to evaluate residential PV system profitability. Huuki et al. (2020) point out that even though moderate IRR or 1-2% is not generally seen as an attractive investment, solar PV is a relatively riskless investment. It could be compared, in essence, to a government bond. From this aspect, other locations than Turku and Oulu could be suitable places to consider solar PV investment.

Recently the literature has started to recognize the environmental values of PV for the producer that can be more valuable than the economic profit. This is shown, for example, by Karjalainen and Ahvenniemi (2019) when interviewing grid-connected small-scale PV electricity producers. The majority of 22 respondents reported that they did not consider payback time to be a relevant way to evaluate the investment. Especially environmentally motivated prosumers were not interested in economic benefits. Instead, they were interested in clean, environmentally friendly energy production, even if it would be more expensive than buying the electricity from the grid. Similar results are received from the US (Schelly, 2014).

Theoretically, the costs of carbon are involved in the electricity price: being an EU member, Finnish energy markets take part in the EU's emission trading system (EU ETS). Through this, the feasibility calculations take social costs of carbon automatically into account. Currently, the price of carbon in EU ETS is around 25€. However, the social cost of carbon is calculated to be higher in various studies, i.e. Pindyck (2016) sets the social cost of carbon between 65-85 €, approximately. The economic characters would look better for PV system if the actual social costs of carbon were included in the price. Huuki et al. (2020) estimated that if the CO2 emission allowance price were 50€, the PV system IRR would reach over 3 percent in Northern-Finland, too.

To illustrate the monetary value of the environmental benefits of a PV system, I have calculated the social costs of carbon from the electricity that a household substitutes by solar PV. According to Motiva (2020), emissions from energy production (E) are on average 0.141 kg of CO2 per kWh in Finland. The avoided CO2 emissions are derived by multiplying the expected amount of solar electricity that the system produces for the use of household (excess energy diminished) (x_n) by the emission intensity factor E. After that, the avoided emissions are changed to monetary value by multiplying by the social cost of carbon (SCC).The value of avoided emissions are

$$(E * x_n) * SCC$$

For the smaller system size in Espoo (2,7 kWp) the avoided emissions of using PV are 9.2 tons of CO2. The social cost of carbon is estimated to vary between 24-80€/tCO2 using estimates of Nordhaus (2016) and Pindyck (2016). Following this, the substitution of grid electricity by PV electricity leads to the value environmental benefits varying between 175€ and 581€ for the smaller system size. For the bigger system (5.5kWp), the avoided emissions are 18,5 tons of CO2, making the monetary value of environmental benefits vary between 352€ and 1 172€.

To sum up, the location and the size of the system are crucial factors for the profitability of residential PV systems in Finland. Coastal and southern areas are better for electricity production making the investment more appealing compared to northern and eastern locations. It is essential to size the system efficiently to match the electricity consumption of the household. An oversized system produces a lot of excess energy that is not valuable for the prosumer, but too little system is relatively expensive if the benefits of it remain low. Also, if environmental benefits would be compensated for the prosumer, the PV systems might be viable more often. The profitability calculation should always be done case-by-case when considering the investment.

4 Data

The data used in this thesis are gathered from open sources of Finnish Energy Authority (2020), Official Statistics of Finland (2020b) and European Commission PVGIS (2020b) and further modified into variables describing the variances between distribution system operator (DSO) areas. Figure 4 shows the distribution grid areas for which the data is aggregated. This section introduces the data, shows how they are modified into model variables and explains what the variables describe.

4.1 Solar PV microproduction

To analyse the extent of PV production, I use DSO level technical information from the Finnish Energy Authority (2020), who collects and maintains data on PV capacity (2016-

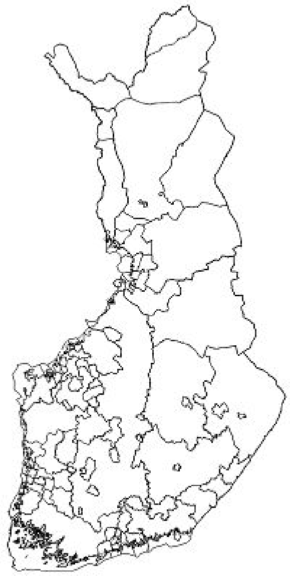

Figure 5: Distribution system operator areas in Finland
Source: Picture supplied by Adato Energia.

2019) and the number of prosumer contracts (2013-2019).

As figure 6 shows, the capacity has grown significantly over the observation period. In 2016, microgeneration capacity was 136 MW and in 2019 it was already more than double: 279 MW.

The total microproduction capacity comes from the different small scale production system streams, such as wind, biomass-based, hydro and solar PV. In 2016 the most significant individual microproduction source by its capacity was diesel. However, as figure 6 shows, the capacity of solar energy has grown massively: in 2016, it was 28 MW, and in 2019 the capacity was already 197 MW. Other microproduction source capacities have remained relatively the same or even decreased over the observation period. This means that the growth in the microproduction capacity is solely from the growing capacity of solar PVs.

The number of prosumer contracts is used to describe the amount of PV installations. Also, the PV capacity is used on some part of the analyses. The benefit of using contracts is that there is more data available since Finnish Energy Authority (2020) has reported prosumer contracts in DSO level since 2013.

The growing popularity of self-produced energy is also visible in the number of prosumer contracts that are highly correlated with PV capacity (0.95). In 2013, the mean number of prosumer contracts per DSO was 2,5, whereas, 2019, the number was already 305. This development is illustrated in figure 7. The DSOs with the most solar PV microproduction are Elenia Oy and Caruna Oy, representing the outliers in the figure 7. In

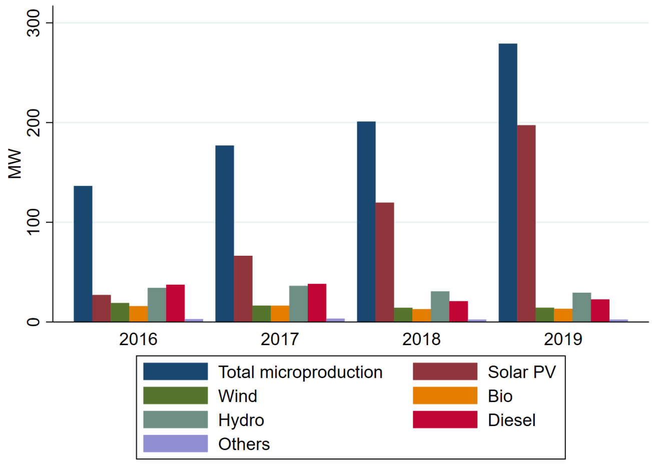

Figure 6: Total microproduction capacity (MW) by generation source between years 2016-2019
Source: Finnish Energy Authority (2020).

2019, Caruna Oy's solar PV production capacity was 46 MW, and the same number for Elenia was 28 MW. The next was Caruna Espoo Oy with 11 MW. These companies also have the highest number of prosumer contracts.

However, the sizes of the DSOs vary remarkably: some have only 139km of grid, whereas the largest DSO's grid length is over 80 000 km. Elenia Oy and Caruna Oy are operating in a large area. Therefore the high number of PV capacity might be skewed by the company size.

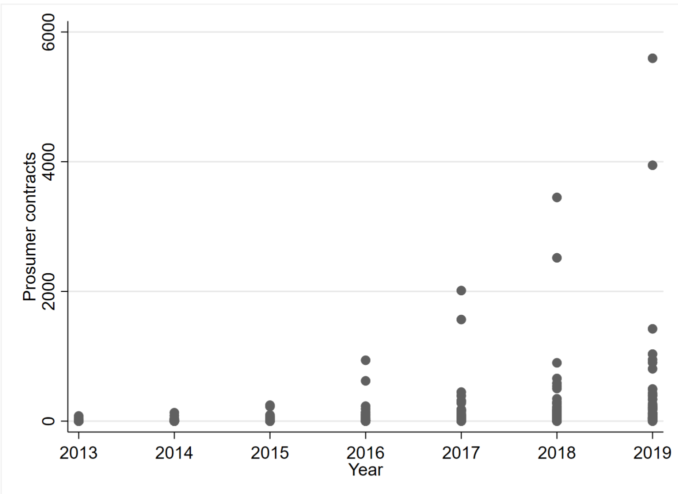

Figure 7: The number of prosumer contracts in DSOs 2013-2018
Source: Finnish Energy Authority (2020).

The model variables are scaled to eliminate the DSO size effect in the analysis. The prosumer contracts are scaled by the number of total contracts. The contract number was chosen to the scalar because it also shows the percentage amount of prosumer contracts of all contracts. The PV capacity is divided by the number of connections in the power grid. The number of connections was chosen because the PV system is installed for each connection, also in the urban areas where there might be many single customers under one connection (e.g., apartment buildings).

Figure 8 shows the distribution of the scaled variables of prosumer contracts and PV capacity. As can be seen, the variables are still skewed to the right, and a considerable variation between DSO areas exists.

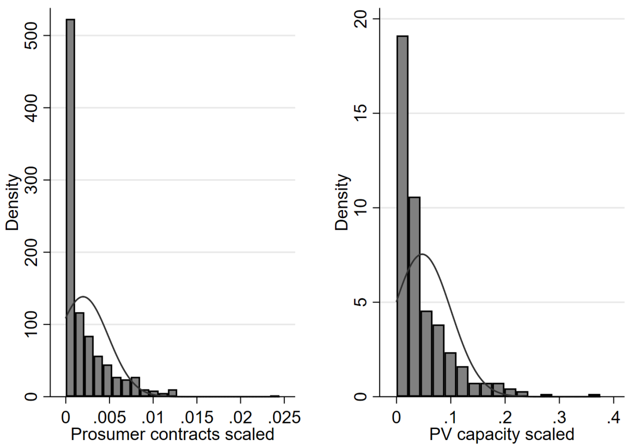

Figure 8: Prosumer contracts and capacity scaled

Source: Own calculations

Note: Prosumer contracts are scaled by the number of total contracts in DSO. PV capacity is scaled by the number of connections in power grid in DSO.

4.2 Electricity prices

As mentioned earlier, the DSOs are regional monopolies and the electricity customer can not tender the distribution price. On the contrary, the source of electricity can be tendered. Therefore, distribution price creates price variances for customers depending on the geographical location and thus is regarded as a valid variable to describe the price in the analysis.

The Finnish Energy Authority (2020) presents distribution prices for each DSO separately in each month since the year 2003. By aggregating the data, a mean price for a company per year between 2013-2019 is derived and used in the analysis. In the original statistics (Finnish Energy Authority, 2020), the distribution prices are divided into ten groups according to the customer type, such as households, farms and industry. The price groups are named as K1, K2, M1, M2, L1, L2, T1, T2, T3 and T4 – these classifications are used in this thesis as well. The analysis focuses on two types of price levels that are the most relevant house types for solar PV production:

- K2 = small detached house with electrical sauna, no electrical heating, use of electricity 5000 kWh/year
- L1 = detached house, room-specific electrical heating, use of electricity 18 000 kWh/year

K1 represents apartment houses and K2 small detached houses with low electricity consumption. They face the highest distribution price level, and the development of these two class are highly correlated (0.86). Thus, I choose to use K2, which correlates more with microproduction compared to K1. L1 and L2 are price classes for detached houses, and they are strongly positively correlated (0.98). L1 represents detached houses with electric heating and a hot water boiler and has stronger correlation with PV capacity and is thus chosen for the analysis.

The other six price classes are for farms and industries. These classes face lower prices than an apartment and detached houses when tax and VAT are included. These price classes are not included in the analysis since this analysis focuses on residential microproduction rather than utility-scale production of industries and farms.

Figure 9 shows the price distribution and development of distribution prices over the observation period. In general, K2 prices are higher than L1 prices. In addition, the K2 class has more variance in the prices between DSOs, whereas L1 prices are relatively similar between DSOs. Both price classes have increased over the years 2013-2019. The mean price of K2 was 7.60 cent/kWh in 2016 and 9.61 cent/kWh in 2019. For L1, the numbers were 5.79 cent/kWh and 7.12 cent/kWh

These prices include tax and VAT. The tax was 2.11 cent/kWh in 2013, 2.36 cent/kWh in 2014 and after that it has remained as 2.79 cent/kWh. VAT is 24% and remained the same the whole observation period. VAT and taxes are not removed from the prices for the analysis because we are interested in the exact price customers face for their electricity distribution.

The highest distribution prices are in DSOs that operate in rural areas, e.g., Savon Voima Oy (14.63 cent/kWh in 2019), Järvisuomen Energia Oy (14.67 cent/kWh in 2019), and Kajave Oy (14.48 cent/kWh in 2019). The high price is correlated with low ground cable level and an increased number of power cuts. These expensive DSO areas are loosely populated and covered with forests and lakes, making ground cable unprofitable, and nature interrupts the power lines constantly. High reparation costs of power lines lead to high distribution prices.

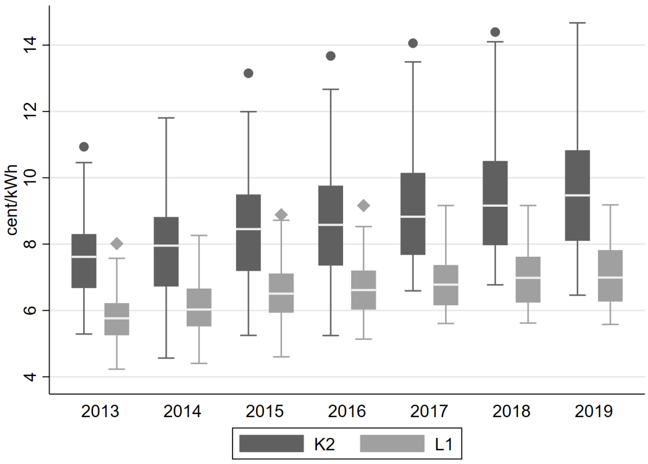

Figure 9: The distribution price distribution and development over the years 2013-2019 for K2 and L1

Source: Finnish Energy Authority (2020)

Note: K2 is the price class for dwellings without electric heating, while L1 is for dwellings with electric heating. Prices include tax and VAT.

On the contrary, the lowest prices are concentrated in urban areas, where power lines are underground and population density is high. In general, the lowest K2 prices are in the companies Turku Energia Sähköverkot (6.93 cent/kWh in 2019), Keravan Energia (7.06 cent/kWh in 2019), and Tampereen Sähköverkko Oy (6.94 cent/kWh). However, there are also low price areas in Lapland, such as Rovaniemen Verkko Oy (6.46 cent/kWh. This might be explained by the willingness to support local settlement and electricity consuming free-time activities such as downhill skiing.

4.3 Settlement variables

Open zip-code level data offered by Statistics Finland Paavo -database is utilized for the settlement structure and socio-demographic variables (Official Statistics of Finland, 2020b). The zip-code level data are gathered from the years 2013-2018 (2019 not available at the time of writing) and combined with DSO data. After that, the data are aggregated from zip-code level to DSO level, and a set of new variables are created to describe the differences between DSO areas best. This is carried out using relative variables, for example, the detached houses' share on the total housing base. The comparable variables underline the areal differences better than just using the absolute amount of detached houses in the area. Table 3 shows the summary statistics for sociodemographic variables

Finland's housing stock consists mainly of small residential buildings, such as detached houses and row houses - up to 53% of people lived in a detached house in 2019 (Official

Table 3: The summary statistics of settlement variables.

Variable	Mean	Std.Dev.	Min	Max
Share of detached houses	0.547	0.127	0.134	0.854
Share of apartment buildings	0.268	0.179	0.010	0.864
Share of summer cottages	0.184	0.108	0.001	0.505
Mean area of dwellings	94.446	8.821	67.534	116.410
Share of owner occupied dwellings	0.703	0.077	0.453	0.829
Share of rented dwellings	0.268	0.081	0.145	0.523
Mean living density	44.188	3.0.45	34.4	50.853
Mean solar radiation	1075	63	927	1209

Source: Own calculations

Notes: All values are in a DSO level over the years 2013-2018.

Statistics of Finland, 2020a). Between 2013-2018, the average share of detached houses was 55% and the share of apartment buildings was 27% over all grid areas. Summer cottages covered 18% of residential buildings. However, there is a considerable variation between DSOs. This implies that some DSOs operate in highly urbanized areas whereas others operate in rural, loosely inhabited regions.

The highest relative number of apartment buildings are concentrated in DSO areas in Southern Finland, where the biggest cities locate such as Helsinki and Turku. On the contrary, the smallest relative number of high-rise buildings is located in rural areas of Finland, such as in middle parts of Finland. The highest relative number of summer cottages is in the area of Naantalin Energia Oy and DSOs in the middle Finland in lake-rich areas. Some DSO areas have almost none summer cottages making the standard deviation high. The variable of summer cottages could be relevant for the analysis because adopting PV system to summer cottages is popular, implying that PV capacity would be higher in DSO areas that have lots of summer cottages. However, some summer cottages might not be connected to electricity grid and therefore all possible PV system installations from summer cottages are not visible is this data. Collecting and analyzing this off-grid PV system data remains interesting opportunity for future research.

Similar conclusions to the housing-type can be drawn when focusing on the mean area of apartments: the small apartments are clustered in Helsinki, and other DSO areas have relatively similar larger apartments. The smallest apartments by square meters are located in Helen Oy operation area (67.5 m^2 in 2018). The biggest apartments are close to the capital area, but not in the urban centers, such as in Etelä-Suomen Energia Oy (115.6 m^2 in 2017). Table 3 shows the summary statistics of apartments' mean areas. A relatively small standard deviation implies that there is not much difference in mean apartment

Table 4: The summary statistics of economic and social variables.

Variable	Mean	Std.Dev.	Min	Max
Share of high income class residents	0.152	0.043	0.078	0.308
Average age	44.403	3.428	34	54.282
Share of households with children	0.213	0.0312	0.119	0.353
Share of people over 65 years old	0.231	0.045	0.125	0.361
Share of adults with graduate degree	0.071	0.036	0.029	0.219
Share of adults with primary school degree	0.263	0.037	0.166	0.333

Source: Own calculations

Notes: Values are in a DSO level over the years 2013-2018, except share of high income class household, which represents only the years 2013-2017 and education related variables where the year 2015 is missing.

areas between DSOs.

It is expected that most of the PV system installations are located in owner-occupied dwellings. The summary statistics of home ownership show that, on average, most of the homes are owner-occupied. Over the observation period, the mean relative owner-occupied dwellings under DSOs was 70%.The numbers are derived by the number of owner-occupied dwellings per DSO over the total number of households. However, there is variation between DSOs.

The mean living density variable describes how big the apartments are compared to the household size in persons, in other words, the variable describes the living area per number of people in the dwelling. On average, the mean living density was $44.2m^2$ between the years 2013-2018 with a standard deviation of 3.2.

4.4 Sociodemographic variables

Similar to settlement variables, the socio-demographic data are collected from Statics Finland Paavo -database. The table 4 shows the summary statistics for socio-demographic variables for the years 2013-2019. Statistics Finland reports the number of residents in the zip-code area that belong to each of the three income classes (low, mid, and high). A resident belonging to the high-income class annual income was over 31 874 €in the year 2017. Unfortunately, the income data is available only until the year 2017. The share of the high-income class residents per DSO is derived by dividing high-income class households by the total number of households. Table 3 shows the summary statistics for this. On average, 15% of the households belonged to the high-income class in DSO areas with a standard deviation of 4.3%. The biggest share of high-income households lived in the area of DSOs that operate in southern Finland, whereas the smallest share of high-income class households is in northern Finland.

The average age for inhabitants in the DSO areas is derived from the mean age in the zip-code area. Summary statistics over the years 2013-2018 are presented in figure 4. The mean for all DSOs was 44 years. In general, the younger average age is in the DSO operating in southern Finland, close to big cities. In contrast, the older average age is in DSO areas operating in northern and eastern Finland.

In addition to the average age, the proportion of over 65-years old inhabitants is included in the analysis (people over 65 / total number of people in a DSO). This age group is chosen because it is the standard retirement age in Finland. As table 3 shows, on average, 23% of inhabitants were over 65-year-old in the years 2013-2018 in DSO areas. There is not much difference between DSOs since the standard deviation is only 4.5%. However, some DSOs represent outliers by having even 36.1% of the population (Koillis-Lapin Sähkö Oy) in the area over 65-year-old. Koillis-Lapin Sähkö Oy has the lowest share of households with children (12%).

The share of households with children shows similar results of age distribution between DSOs. The variable is created by dividing the families with children by the total number of households in the DSO area. Oulun Energia Siirto ja Jakelu Oy operated in an area where even 35% of households have at least one child. Again, the smallest proportion of families with children are in the northern parts of Finland.

The education of the population does not divide equally between DSO areas. The share of adults with a graduate degree (master's level) is, on average, 7.1% with a standard deviation of 3.6%. The highest percentage of graduate degrees are in Southern-Finland. Namely, in the operation area of Helen Oy, 21.9% of adults were graduated with a higher degree of education in the year 2018.

In addition to a graduate degree, the share of inhabitants with only primary school degrees is involved in the analysis. On average, 26.3% of the population belonged to that group, with a standard deviation of 4.3%.

5 Analysis

The following chapter presents the result of the descriptive analysis and regression analysis. The correlations between contracts, capacity and the model variables are represented in table 5 and 6 and analysed in section 5.2. More detailed correlations between all model variables are in the Appendix B, from which the most important correlations are highlighted in section 5.1. Finally, the regression model and results are presented in the section 5.3 and table 7.

5.1 Correlations between explanatory variables

This section analyses the correlations between explanatory variables relating to settlement, socio-demographic and geographical factors, and electricity price. The table of all model variable correlations is in the Appendix B.

There is a strong negative correlation between apartment buildings and detached houses (-0.81) and summer cottages (-0.71). The result is expected because some DSOs are centered in urban areas while others operate only in Finland's rural parts. Another variable that describes the urbanization level is the mean share of people living in a rented apartment that is highly positively correlated (0.92) to the mean share of building apartments.

Similarly, the variables describing the area's rurality are the share of detached houses and the share of owner-occupied dwellings, which are highly positively correlated (0.83). Also, the mean area of the dwellings (0.72) and the average living density in a house (0.462) are moderately correlated to the share of owner-occupied dwellings. It can be interpreted that where people live in owned homes, the house area is bigger, but the number of family members is higher, decreasing the average living density in a house.

The average age of the people living in DSO areas is correlated positively to the share of people over 65 years (0.78), the share of summer cottages (0.70) and the average living density in a house (0.75). It can be interpreted that older people are clustered in DSO areas in the rural part of Finland. Also, the age variables have a strong negative correlation with the share of master's level graduates in the area (-0.74 with pensioners). Similarly, the share of people who have just comprehensive school degrees is positively correlated with pensioners' share in the area (0.70).

The high-income variable is correlated with the share of master's level graduates (0.29) and the share of building apartments (0.42). Also, high-income has a negative correlation with the average age of the area (-0.59). This implies that the higher income class share is higher in urban areas, where the population is relatively young and educated.

The distribution prices K2 and L1 are positively correlated (0.95). The prices are the most correlated with mean living density variables in a house (0.60 & 0.54) and pensioners' share (0.58 & 0.57). There is a moderate negative correlation with typical variables for urban areas, implying that the distribution prices may be higher in the areas where people live commonly in owner-occupied dwellings, and the share of summer cottages is relatively high.

5.2 Descriptive analysis

Next, correlations between the prosumer contracts, PV capacity and explanatory variables are analysed and interpreted in the light of previous literature. The section is divided so that settlement structure variables are analysed first, then sociodemographic variables and finally electricity price and irradiation level.

5.2.1 Settlement structure

The settlement structure variables show opposite correlations with capacity and the number of contracts. Variables typical for urban areas are positively correlated with PV capacity, such as the share of apartment buildings (0.51) and the share of people living in rented apartments (0.47). On the contrary, the variables distinctive for rural areas are connected to the number of contracts. For example, the mean living density and the mean area of a house have a moderate positive correlation to contracts (0.27). Simultaneously, the share of owner-occupied apartments (0.07) and the share of detached homes (0.08) are mildly positively correlated with the prosumer contracts.

Similarly, the literature does not give a straight-forward conclusion on how the settlement structure is connected to the PV installations. Some studies suggest that house density is positively correlated with adopting a residential PV system (Schaffer and Brun (2015); Kwan (2012)). On the other hand, Graziano and Gillingham (2015) find a negative connection between urban areas and PV uptake. Some studies do not see any apparent link to the settlement structure (Dharsing, 2017).

A recent study from Finland offers similar results as the connection between contracts and settlement structure here. Ruokamo et al. (2020) find that the adoption of PV systems is more common in the rural areas (adopter lives in the countryside or small village). The home size is also positively connected to the PV adoption likelihood, similarly to the house mean area in my analysis.

One plausible interpretation is that the urban area PV system sizes are significantly larger than in rural areas. According to Ruokamo et al. (2020), microproduction is still more common in rural areas, which is also visible as a number of contracts in my data. In other words, the household level microproduction seems to be centered on rural areas. In contrast, there are not that many separate producers in urban areas, but single systems' capacities are more extensive. The bigger cities have also ambitious carbon neutrality goals; for example, Helsinki aims to be carbon neutral in 2035 and to produce 15% of the electricity from solar. The city has already invested in PV systems for, e.g., schools and hospitals, and plans to increase the capacity even more in the future. (City of Helsinki, 2018). This kind of development can explain the capacity increase in DSOs operating in urban areas.

Another explanation is that a high relative number of, for example, apartments buildings, is correlated to omitted variables. The culture, attitudes, and social networks might be more favorable for solar PV in the areas close to urban centers. Indeed, the social acceptance of renewable technologies in the area of Helsinki is considerably high. According to a survey study on the Helsinki metropolitan area by Jung et al. (2016), solar panels were the most popular renewable technology. Respondents showed a strong willingness to pay and use their roof or backyard area for energy production: only eight of 264 respondents selected that they do not wish any renewable energy technology on their property (Jung et al., 2016).

The importance of the network is supported in previous literature, too. Hai (2019) and Vasseur and Kemp (2015) suggest that a lack of proper information and support networks obstructs solar PV system adoption. The location close to urban centers and dense inhabitants may allow better information exchange compared to rural areas. The so-called peer-effect is also visible in the study of Ruokamo et al. (2020). They found that having an acquaintance invested in a PV system increases the probability of investing. In addition, not having enough relevant information on PV systems for households was connected to being a considerer instead of investing in one (Ruokamo et al., 2020).

In urban and more densely habitat areas, the information and supply of PV systems might be better available than in rural environments. This could affect the trend that the capacity of PV systems seems to cluster in urban DSOs.

To sum up, the variables distinctive for rural areas are connected to prosumer contracts, whereas PV capacity is correlated with urban variables. However, the data set restrictions on how far we can interpret the relationship between microproduction and settlement structure. The data vary a lot between zip-codes under one DSO, even in Finland's most urbanized parts. To have a more consistent study on settlement structure connection to PV uptake in Finland, the zip-code level data on PV capacity is crucial.

5.2.2 Sociodemographics

The share of households belonging to the highest income class is mildly positively correlated with the number of contracts (0.13). However, when focusing only on the last three years of the observation period (2016-2018) the correlation is negative (-0.27). This implies that the recent increase in prosumer contracts is rather negatively connected to the income level.

These results are surprising in the context of previous literature, where adopter is typically characterized as wealthy or with high socio-economic status (Borenstein, 2017; Kwan, 2012; Dharsing, 2017; Vasseur and Kemp, 2015). High income is considered a critical factor affecting the adoption decisions because of the PV system's high investment costs. Instead of the prosumer contracts, the data show a positive relationship between capacity and the highest income class (0.35). One explanation for the difference between correlations could be that the PV capacity is clustered in the urban areas, as concluded earlier, and these areas are correlated with the high-income level. Again, the aggregated data limits the possibility to see real patterns between socio-economic status and PV

Table 5: Correlations of model variables

Settlement structure	Capacity 2016-2018	Contracts 2016-2018	Contracts 2013-2018
1. PV capacity	1.00	0.21	0.21
2. Apartment buildings	0.51	−0.13	−0.07
3. Detached houses	−0.40	0.17	0.08
4. Summer cottages	−0.38	0.02	0.02
5. Mean area of a house	−0.28	0.13	0.10
6. Owner-occupied apartments	−0.44	0.16	0.07
7. Rented apartments	0.47	−0.13	−0.04
Socio-demographics			
8. Mean living density	−0.35	0.21	0.27
9. Highest income class	0.34	−0.27	0.13
10. Graduate degree	0.45	0.01	0.08
11. Elementary school	−0.32	−0.02	−0.18
12. Mean age	−0.33	0.10	0.14
Irradition & Price			
13. Mean irradiation	0.09	0.15	−0.01
14. Price K2	−0.21	0.25	0.35
15. Price L1	−0.20	0.22	0.35

Correlations between model variables over the observation periods

Source: own calculations

system adoption.

Education variables act quite similarly to the income class. PV capacity is positively correlated with the share of people having graduate degrees by 0.45, and prosumer contracts by notably more weakly (0.08). Similarly, the share of people with only comprehensive school degree is negatively correlated to PV capacity (-0.32) and prosumer contracts (-0.18). Again, the difference between capacity and contracts might be related to the urban environment where systems are more extensive. Highly educated people might more often have the financial capability to invest in PV systems, which is implied by a strong correlation between education and income variables.

The positive connection can also be explained by the fact that people with graduate degrees might be more exposed to information about solar PV systems and their climate benefits and more likely to adopt one themselves. Indeed, the literature suggests that a significant factor in PV adoption seems to be environmental concerns. For example, Jung et al. (2016) showed in their survey study that people who selected to be interested in saving energy and environmental resources were willing to invest over 6000€ in renewable energy technology. On the contrary, among the people who felt that climate change doesn't affect them personally, only 14% were willing to pay any monetary amount (>1000€) (Jung et al., 2016). Similarly, Ruokamo et al. (2020) observed that PV adopters are more likely to account for environmental aspects in investment decisions, and non-adopters are positively connected to climate-skeptic statements.

This thesis' data cannot directly distinguish the effect of environmental values and attitudes to PV capacity or prosumer contracts in DSO areas. In theory, a variable based on voting behavior could be created, for example, the share of people in the area who have voted green party. However, other studies based on statistical analysis on observed data haven't found any significant connection between voting action and PV adoption (Schaffer and Brun, 2015; Dharsing, 2017). Instead, the relationship between environmentalism and PV adoptions is observed in studies using interviews and surveys (e.g. Balcome et al. (2013); Karjalainen and Ahvenniemi (2019); Nygren et al. (2015)).

The mean age of people in DSO is ambiguously related to microproduction. PV capacity seems to be moderately negatively correlated to mean age (-0.33). This fits the earlier conclusions that PV capacity is centered in the areas close to the urban areas where people are often relatively young. However, the prosumer contracts have a positive connection to the mean age (0.14), implying that areas with older mean age have a higher share of prosumer contracts. The literature links the age and PV installations with an u-shaped curve (Kwan, 2012; Leenheer et al., 2011; Balcome et al., 2013). PV installations are most common in the age of 35-45 when the purchasing power is typically the greatest. Balcome et al. (2013) underline that younger people are environmentally oriented and open to investing in renewable energy technologies, but the financial situation can be a barrier. On the contrary, people close to retirement age might have financial resources and property, but the lack of information and interest is a barrier to investment.

To summarize, the prosumer contract variable seems to be somewhat in line with a recent survey-study from Finland (Ruokamo et al., 2020). It looks like microproduction is related to older age and lower-income. On the contrary, the PV capacity is connected to areas with a higher share of educated and high-income residents. However, these areas are typically urban centers, where single PV system sizes might be more prominent, and other factors might affect the result, facing the omitted variables challenges in my analysis.

5.2.3 Electricity price and irradiation

As concluded earlier, the electricity price and irradiation level significantly influence the PV system's profitability. Thus, it is expected that there is a positive correlation between

Table 6: Correlations of microproduction and prices

Distribution prices	1	2	3	4
1. Prosumer contract	1.00			
2. PV capacity	0.21	1.00		
3. K2	0.35	−0.21	1 00	
4. L1	0.35	−0.20	0 92	1.00

Source: own calculations

these variables and microproduction.

The price levels of K2 and L1 are moderately positively correlated with prosumer contracts (0.35). A higher price of electricity incites investing in self-sufficient electricity production. Moreover, the high price level is connected to the amount of disturbance in electricity supply: frequent cuts in electricity and unreliability of the electricity supply might urge to install a PV system.

The study of Ruokamo et al. (2020) shows similar results: the expectation of future electricity rise will increase the likelihood of PV system adoption. Also, the electricity price will affect the profitability of PV system investment as was found in the section 3.3.2. Ruokamo et al. (2020) found out that the PV system's payback time is considered more often too long among non-adopters so increase in the profitability could enhance PV system adoptions.

However, PV capacity seems to have a negative connection to the price levels (-0.21). The capacity growth could be influenced by other than financial reasons. As concluded earlier, the environmental concern is one of the most commonly stated reasons for installing or consider installing a PV system in survey studies in Finland (Karjalainen and Ahvenniemi, 2019; Nygren et al., 2015). The recent PV capacity growth clusters are close to the urban centers, where the typical PV system might be more extensive than in rural parts of Finland, despite the price-level.

Somewhat surprisingly, mean irradiation seems to have only a small positive correlation to PV capacity (0.09) and almost no correlation to prosumer contracts (-0.01). Prior studies suggest that solar radiation can be identified as an essential driver of installed capacity (Schaffer and Brun, 2015; Dharsing, 2017). As a relatively long country, the irradiation level varies a lot: in southern Finland and coastal areas, the irradiation is higher than in the northern and eastern parts of Finland. One explanation for why the irradiation level doesn't show a significant connection to the microproduction level is that the data is too aggregated. The irradiation levels can vary a lot locally, and when aggregating the data from mean zip-code irradiation to DSO level, a lot of important information are lost.

For example, the irradiation for Caruna Oy is on average 1085 kWh/m2/year, but the values vary between 905 and 1247 kWh/m2/year.

To conclude, the descriptive analysis showed that there is a moderate positive correlation between prosumer contracts and electricity price and, on the contrary, the capacity variable was negatively connected to electricity price. No clear connection between solar irradiation and microproduction was found.

5.3 Regression analysis

The data are further analysed by multiple linear regression that is a statistical technique for modeling a linear relationship between explanatory variables and a response variable. This method is chosen because it is good and simple tool to study linear relationships between variables and it fits well to the panel data with continuous explanatory variable. The multiple regression model is generally represented as follows (Stock and Watson, 2020):

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + ... + \beta_k X_{ki} + u_i, i = 1, ..., n \tag{1}$$

Where Y_i is i:th observation of the dependent variable; $X_{1i}, X_{2i}, ..., X_{ki}$ are the i:th observation on each k regressors; and u_i is the error term. β_k are coefficients that describe the partial effect on Y of X_i, holding other regressors X fixed. β_0 is the constant term that is the expected value of Y when all X's are equal to 0.

The regression line is estimated from the data by ordinary least square method (OLS), which estimates the regression line as close as possible to observed data. More specifically, by applying OLS coefficients β_i are estimated by minimizing the sum of squared prediction mistakes. This happens by choosing values of $b_0, b_1, ..., b_k$ that minimize $\sum_{i=1}^{n}(Y_i - b_0 - b_1 X_{1i} - ... - b_k X_{ki})^2$ (Stock and Watson, 2020). The estimators that do that are OLS estimators noted as $\hat{\beta}_0, \hat{\beta}_1, ..., \hat{\beta}_k$. The OLS predicted values for the dependent variable $\hat{Y}_i$ are (Stock and Watson, 2020):

$$\hat{Y}_i = \hat{\beta}_0 + \hat{\beta}_1 X_1 i + ... + \hat{\beta}_k X_{ki}, i = 1, ..., n \tag{2}$$

and for residual u are $\hat{u}_i$:

$$\hat{u}_i = Y_i - \hat{Y}_i, i = 1, ..., n \tag{3}$$

The OLS estimators are estimators of the unknown coefficients $\beta_o, \beta_1, ..., \beta_k$ and error term u_i. They are derived from a sample of n observations of regressors $(X_{1i}, ..., X_{ki}, Y_i), i = 1, ..., n$. (Stock and Watson, 2020)

The multiple linear regression and OLS are based on some assumptions that make the model possible and unbiased. First, the conditional mean of error term has mean of 0.

Second, regressors are independently and identically distributed random variables. Third, large outliers are unlikely. Finally, there is no perfect multicollinearity between regressors. (Stock and Watson, 2020).

To see the methodology of multiple linear regression and OLS in more detail, see Stock and Watson (2020). Next, the multiple linear regression model is applied to the thesis' data.

5.3.1 Model

In this thesis the multiple regression model links the share of prosumer contracts to electricity price, settlement characteristics and sociodemographic variables at the DSO level.

The model focuses on the prosumer contracts instead of capacity because, as concluded earlier, there are more observations available. The downside is that straight interpretations of PV on the ground of prosumer contracts cannot be made since it includes other microproduction sources, too. However, the development of PV capacity and prosumer contracts have been highly correlated implying that the recent years growth in prosumer contracts is mainly from the solar PV. For the analysis, the share of prosumer contracts is scaled by 100 so that the results can be interpreted as percentage points.

The electricity distribution price K2 is considered an important model variable because, as an unaggregated variable, K2 describes the price level's actual variation between DSOs. Also, the price of electricity was concluded to impact the PV system's economic viability; if households are attentive to the costs of PV system, a higher electricity price should increase the share of prosumer contracts.

The choice of other model variables was more difficult because of the high correlation between socioeconomic and settlement variables. To avoid multicollinearity, I picked just a few variables that best describe the possible connection with PV adoption according to previous literature. The share of detached houses from all dwellings was chosen to describe the settlement structure of the area, the share of pensioners reveals the age structure and the share of adults with graduate degree describes the socioeconomic status. However, the data for the education level is missing from the year 2015, decreasing the number of observations of the final model.

The model includes fixed-effect to avoid heterogeneity bias that might occur from imposing a common constant term. More specifically, it is assumed there are crucial omitted variables related to the geographic and sociodemographic factors that the data can not capture. These omitted variables might be the availability of information, favorable culture, and single system sizes (i.e. system capacities are larger in urban areas). Urban fixed effect (U_{it}) is included to distinguish the analysis from the variables that are not available. The ground cabling level defines urbanization: a DSO is defined as urban if at least 65% of the mid-voltage grid is underground. The cabling level is suitable because

DSOs operating in urban areas have to build the grinds underground. Instead, in the areas of dispersed settlement, ground cabling of the mid voltage grid is not typical.

The year fixed-effect in panel data is used to remove the time-related trend effect on explanatory variable Y_{it} of year t. To address heteroscedasticity, robust standard errors were used.

The model can be written as:

$$Y_{it} = \alpha_0 + \beta_K * X_{Kit} + \delta * U_{it} + \gamma * T_t + u_{it} \tag{4}$$

where i is the DSO (77 in total), and t is the year (2013-2018) of specific observation; Y_{it} is the share of prosumer contracts; X_{Kit} is model variables K defining the variables for electricity price, share of detached houses, share of pensioners and adults with graduate degree; U_{it} is the control variable for urbanity; T_t is the dummy variable for years; and ϵ_{it} is the error term.

The coefficients α_0, β_K, δ and γ are estimated using OLS method minimizing the sum of squares of predicted mistakes as explained in the last section. The software STATA was used to obtain the results.

5.3.2 Results

Table 7 summarises the results of regression explaining the share of prosumer contracts in a DSO. There are in total four models, each column representing a model that includes different numbers of explanatory variables. The marginal effects of final model variables are presented in figure 10

The first model includes the distribution price K2, the share of detached houses and people over 65. Also, the fixed effect for an urban grid is included. Only K2 is statistically significant ($p<0.001$), positively affecting the share of prosumer contracts, while other model variables are not statistically significant. Adjusted R^2 is relatively low in the first model, only 11.5%, implying that the model does not explain the variation of the explanatory variable well.

Adding the time fixed-effect to the model increases the adjusted R^2 from 11.5% to 49%. From 2016 on-wards, the increase in prosumer contracts is statistically significantly different from the base year 2013. Adding time fixed-effect decreases the effect of K2. However, still staying positive and significant at a 5% confidence level. Also, the share of people over 65 negatively impacts prosumer contracts (at 5% level), similarly to the control variable for urbanity (at 1% level).

The control variables can not be interpreted as other variables since they clear the model from omitted variable bias rather than being explanatory variables. Instead, by examining interaction terms, we can interpret how other model variables act if omitted variables are controlled. Therefore models 3-4 include interaction terms.

Overall, it seems that urbanity has a statistically significant effect on the marginal impacts of variables K2 and pensioners. The interaction term of K2 and urban shows that the effect of K2 on the share of prosumer contracts is weaker in the areas categorized as urban. In non-urban areas, an increase of 1c/kWh in distribution costs will increase the share of prosumer contracts by 0.017% points. In relation to the overall mean share of prosumer contracts (that is 0.13%), this is an increase of 13%. If the area is defined as urban, the marginal effect would be negative by -0.042% points, making the percentage reduction in contracts 32%. The price's impact is still relatively similar compared to e.g., Kwan (2012), who observed a 21.7% increase in residential solar PV share predicted for every 1c/kWh (USD) increase of electricity cost.

For the pensioner variable, the effect of urbanity is more substantial: a one-unit increase in the share of people over 65 years would decrease contracts by -0.54% points if urban=0 and increase the contacts 0.77% points if urban=1. The detached house variable is not statistically significant, and neither is the interaction term.

Finally, the share of adults with a graduate degree is added to model four. Note that the number of observations is now smaller since 2015 is missing from the education data. The final model implies that electricity price and the share of detached houses affect the share of prosumer contracts, controlled by the years and urbanity. Urban areas are now less connected with the sociodemographic and settlement variables; for example, the share of pensioners and detached houses does not significantly affect prosumer contracts when urban=1. The share of graduate degree would have a more substantial impact on rural areas than urban, but the variable is not statistically significant. The marginal effects of model variables are presented in figure 10.

Table 7: Regression analysis results

	(1) Contracts	(2) Contracts	(3) Contracts	(4) Contracts
K2	0.0463***	0.0149**	0.0170**	0.0167*
	(0.0064)	(0.0048)	(0.0052)	(0.0068)
Detached houses	0.0720	0.0446	0.0370	0.4098*
	(0.0786)	(0.0615)	(0.0821)	(0.1783)
Pensioners	-0.2668	-0.4747*	-0.5460*	1.0415
	(0.2857)	(0.2249)	(0.2695)	(0.8715)
1.urban	-0.0050	-0.0918***	0.0412	0.9014*
	(0.0259)	(0.0265)	(0.1292)	(0.3760)
1.urban.K2			-0.0600***	-0.0433*
			(0.0140)	(0.0170)
1.urban.detached			0.1139	-0.4040
			(0.1404)	(0.2403)
1.urban.pensioners			1.3233**	-0.6102
			(0.4374)	(0.9140)
Graduate degree				3.5536
				(2.2625)
1.urban.graduate				-3.9622
				(2.2067)
2014		0.0027	0.0030	-0.0097
		(0.0065)	(0.0063)	(0.0118)
2015		0.0111	0.0118	
		(0.0092)	(0.0093)	
2016		0.1346***	0.1368***	0.0758***
		(0.0389)	(0.0399)	(0.0182)
2017		0.2251***	0.2295***	0.1830***
		(0.0197)	(0.0205)	(0.0267)
2018		0.3896***	0.3938***	0.3335***
		(0.0282)	(0.0289)	(0.0377)
_cons	-0.2402*	-0.0217	-0.0204	-0.8031*
	(0.0968)	(0.0905)	(0.1183)	(0.3910)
N	465	465	465	389
adj. R^2	0.115	0.490	0.493	0.516

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

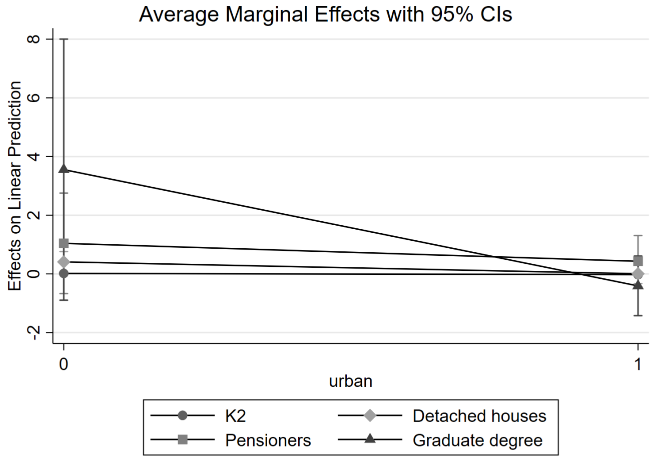

Figure 10: Margins plot for variables in model 4
Source: Own calculations

6 Discussion

In this section, I will discuss the findings in the light of previous literature, the limitations of the thesis and implications for policy-makers.

The analysis showed that, overall, the relationships between the variables describing the settlement structure, sociodemographics, and price- and irradiation levels in DSO areas behave differently with PV capacity and prosumer contracts. The recent growth of the PV capacity is clustered in urban DSOs where housing is concentrated to apartment buildings, the mean age is relatively younger, a bigger share of people have graduate degree, income level is higher and electricity distribution price is lower. Similar findings have been made in studies outside of Finland (e.g. Balcome et al. (2013); Borenstein (2017); Kwan (2012); Vasseur and Kemp (2015)). However, it is reasonable to note that much larger system sizes can influence the capacity in urban areas, where PV systems are installed on the hospitals, schools and malls in addition to residential buildings.

Unlike the PV capacity, the results from analyzing prosumer contracts are in line with recent study of solar PV prosumers under one of Finland's biggest DSOs: the study of Ruokamo et al. (2020) implies that rural areas, lower income and education level, and environmental values are increasing the likelihood to adopt solar PV system. Similarly, this thesis found a positive correlation between prosumer contracts and settlement structure and price level typical for rural areas. The regression analysis showed that electricity price and the share of detached houses affect the share of prosumer contracts. The multiple linear regression model was controlled by urbanity as there are expected to be important omitted variables related to the closeness of big cities, such as availability of information and peer-support, that the data can not describe. By studying margins between urbanity indicator variable and other model variables, it was shown that the electricity price has a negative effect on prosumer contacts when DSO operates in urban areas, whereas otherwise, the effect is positive.

The aggregation of data sets some limitations on how strong interpretations can be made from the analysis. The results of the thesis show that the characteristics related to microproduction of solar PV are complex and involve various interactions that are difficult to capture in aggregated data. An opportunity for future research is therefore to repeat the analysis with a more detailed geospatial dataset, for example, by collecting zip-code level PV capacity or contract information. Another limitation of this thesis is the relatively short timeline of observations. Production of solar energy has grown significantly but the total production is still a minor part of energy production entity, consequently, the available data can describe mainly early adopter of a novel technology. New data in the coming years, especially after the needed changes in legislation related to housing co-operatives and net-metering, will allow more extensive and solid analysis on characteristics connected to microproduction of solar PV.

A few policy implication based on the thesis findings and previous literature are suggested: financial incentives and updated information and regulations on residential solar energy production.

The profitability calculations showed that the solar PV system is not a viable investment in most of the locations in Finland. Moreover, the regression analysis showed that the electricity price has a significant impact on the microproduction of electricity, implying that financial reasons are playing a role in the adoption decision of solar PV system, which is supported by previous studies (e.g. Balcome et al. (2013); Karjalainen and Ahvenniemi (2019). Also, Ruokamo et al. (2020) found that the potential adopters in the consideration stage seem to consider the system adoption economically unappealing and would be in favor of government support, even though the adoption motivations would be environmental. Currently, Finland is relying on market-based development of solar energy and it might be enough to reach the solar energy goals if the system's prices keep decreasing. In addition, expected rise of electricity prices in the 2030's, due to integration of European electricity markets and decreasing capacity of nuclear power, may incite households to become prosumers (Ministry of Economic Affairs and Employment of Finland, 2019). However, policy-makers could ease various uncertainties involved household's investment decision by making clear financial incentives for microproduction. For example, if carbon would be priced correctly leading to contaminant energy being more expensive, the profitability of PV systems could reach viable levels.

Another major factor affecting the PV adoption is the availability of information and peer-experience: offering information networks and making regulations simple and unified could enhance the adoption. Recent studies from Finland (Jung et al., 2016; Hai, 2019; Ruokamo et al., 2020) have shown that access to reliable and updated information is vital for adoption decisions. Often prosumers already know someone else, that has invested in solar PV systems which lower the barrier to adopt one yourself. For example, municipalities could offer reliable information for households or arrange platforms for potential adopters to get households started with solar energy production.

Updating regulations and unifying rules of microproduction are crucial. There are already steps in the right direction: a recent decree on the housing cooperatives microproduction will allow single households to do small-scale energy production for their own use, similarly as other households have been able to do already (Finnish Government, 2020). This will open the PV system adoption decision to 47% of people who are currently living in apartment buildings and row houses. The same decree will unify regulation on metering, which previously lead to unequal treatment of prosumers under different DSOs. At the latest in the year 2023, all DSOs must use net metering, which will minimize the electricity sold to the grid gaining economic advantages to prosumers. These kinds of corrections and simplifications to regulations are necessary to lower the barrier of microproduction of electricity.

7 Conclusions

The purpose of this thesis was to gain insights on residential microproduction of solar electricity in Finland. The topic is important, because the capacity of microproduction of solar PV and the number of prosumer contracts has grown enormously in recent years in Finland. Nevertheless, there is a lack of country-level statistical analysis on the topic.

The research question was which sociodemographic, economic and geographical factors are connected to the microproduction of solar PV in Finland. The question was approached by literature review and statistical analysis. The data for the analysis was gathered from open sources of Finnish Energy Authority (2020), Official Statistics of Finland (2020b) and European Commission PVGIS (2020b), followed by aggregating the data on DSO level. The dependent variable was the number of prosumer contracts, explained by the variables describing area's sociodemographic characteristics, settlement structure, solar irradiation and electricity price. The data was analysed, first, by a descriptive manner looking at correlations. This was followed by regression analysis, using multiple regression model and OLS method.

Based on the analysis, the rural areas, older age and high electricity distribution price are connected to microproduction of solar PV. Education and income showed moderate correlation with prosumer contracts; however, regression analysis did not find them having statistically significant impact on the prosumer contracts. These findings are in line with the recent literature from Finland. Urban areas seemed to behave differently, therefore it is expected that there are some omitted variables related to urbanity, which the available data can not capture. Based on previous literature, these omitted variables could be favorable culture and availability of information.

In addition to prosumer contracts, the capacity of microproduction of solar PV was analysed. It was found that the recent growth of PV capacity concentrates in urban DSOs and areas where the population is relatively young, educated and distribution price is lower, contradicting with the results from prosumer contracts. The difference in findings are explained most likely with the larger size of PV systems in urban areas, where, for instance malls, act as prosumers.

The thesis' limitations are in highly aggregated data and in still relatively small number of observations. By analysing the data on DSO level a lot of information is lost. For example, there are a lot of variation in settlement structure under one DSO, as the geographical operation area is large making it difficult to link what kind of settlement is actually connected to the microproduction of solar PV. Thus, strong interpretations can not be made, even though the thesis gives relevant introductory results and comprehensive overview on the current situation. Also, residential microproduction is still a new phenomenon and the data describe more early adopters than the potential majority. These limitations leave interesting research opportunities for the future to repeat the analysis with geospatially more detailed data with larger number of observations.

To understand the context where prosumers act, the thesis also had an overview on policy framework, geographical potentiality, and PV system's installation and profitability. To summarize, a prosumer has to buy the PV system that consist of panels and an inverter, and take care of the contracts with local DSO and an electric company where to sell the excess electricity, or alternatively, have a storage system. The profitability calculations showed that the economic viability depends on various factors, especially the level of irradiation in the area, the price of the electricity and the ability to utilize produced electricity on-site. Overall, with realistic assumptions, the PV systems are still not profitable investment for a household in Finland.

There is political will to increase the share of solar energy as a part of decarbonization of energy production. Nevertheless, no binding targets for solar energy are set and the residential production relies on market-based development. However, based on the findings of the thesis, financial incentives could help potential prosumers to invest in solar PV system and overcome the existing financial barriers. Maybe even more importantly, offering up-dated information and peer-support could increase the residential PV uptake.

I am looking forward to see how the latest changes in net-metering and housing cooperation's regulation will affect on microproduction of solar PV. Also, on-going smart energy transitions makes active participation to energy markets crucial growing the importance on prosumers. Residential solar PV production remains interesting and potential part of the decentralized and clean energy production leaving a lot to study in the future.

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Appendices

A Profitability Calculations

	K2 Espoo	K2 Turku	K2 Jyväskylä	K2 Joensuu	K2 Oulu	K2 Rovaniemi	K2 Espoo High dist.	K2 Espoo Low dist. Price
Electricity costs from the grid								
Electricity price snt/kWh (includes tax)	7,18	7,18	7,18		7,18	7,18	7,18	7,18
Distribution price snt/kWh (no tax)	4,502	4,502	4,502		4,502	4,502	2,12	8,36
Tax for distribution snt/kWh	2,794	2,794	2,794		2,794	2,794	2,794	2,794
VAT % of distribution	24 %	24 %	24 %		24 %	24 %	24 %	24 %
Estiamated yearly price increase %/year	2,5 %	2,5 %	2,5 %		2,5 %	2,5 %	2,5 %	2,5 %
Technical information of PV system								
Power output kWp	2,7	2,7	2,7	2,7	2,7	2,7	2,7	2,7
System size m^2	18	18	18	18	18	18	18	18
Irradiation kWh/m^/year	1122,46	1284,05	1122,46	1071,5	1122,46	1122,46	1122,46	1122,46
Output according to irradiation kWh/kWp	883,81	1024,66	883,81	836,05	883,81	883,81	883,81	883,81
Electricity output in the beginning kWh	2386,287	2766,582	2386,287	2257,335	2386,287	2386,287	2386,287	2386,287
Output decrease %/year	-0,5 %	-0,5 %	-0,5 %	-0,5 %	-0,5 %	-0,5 %	-0,5 %	-0,5 %
Share of excess electricity produced %	25 %	25 %	20 %	20 %	20 %	15 %	25 %	25 %
Price that excess electricity is sold snt/kWh	2	2	2	2	2	2	2	2
Lifetime of PV system	30	30	30	30	30	30	30	30
Costs of the PV system								
Investment cost €	6000	6000	6000	6000	6000	6000	6000	6000
Subsidy (household tax refund)	900	900	900	900	900	900	900	900
Rate of return	3 %	3 %	3 %	3 %	3 %	3 %	3 %	3 %
Costs of changing the inveret % of investment cost	8 %	8 %	8 %	8 %	8 %	8 %	8 %	8 %
Maintenance costs	100	100	100	100	100	100	100	100
Profitability								
Value of production	11 876 €	13 769 €	11 977 €	12 281 €	12 494 €	11 699 €	15 497 €	9 640 €
Total costs of the system	9 480 €	9 480 €	9 480 €	9 480 €	9 480 €	9 480 €	9 480 €	9 480 €
NPV	- 733 €	468 €	- 669 €	- 476 €	- 341 €	- 845 €	1 565 €	- 2 151 €
IRR %	2,10 %	3,55 %	2,18 %	2,42 %	2,59 %	1,96 %	4,76 %	0,15 %
Payback time (years)	>30	25	>30	>30	>30	>30	24	>30
	Change in location						Electricity distribution price changes	

Figure 11:

	K2 Espoo	L1 Espoo		L1 Espoo	L1 Turku	L1 Jyväskylä	L1 Joensuu	L1 Oulu	L1 Rovaniemi		L1 Espoo, High dist.	L1 Espoo, low dist. Price
Electricity costs from the grid												
Electricity price snt/kWh (includes tax)	7,18	6,57		6,57	6,57	6,57	6,57	6,57	6,57		6,57	6,57
Distribution price snt/kWh (no tax)	4,502	2,184		2,184	2,184	2,184	2,184	2,184	2,184		4,18	1,47
Tax for distribution snt/kWh	2,794	2,794		2,794	2,794	2,794	2,794	2,794	2,794		2,794	2,794
VAT % of distribution	24 %	24 %		24 %	24 %	24 %	24 %	24 %	24 %		24 %	24 %
Estiamated yearly price increase %/year	2,5 %	2,2 %		2,2 %	2,2 %	2,2 %	2,2 %	2,2 %	2,2 %		2,2 %	2,2 %
Technical information of PV system												
Power output kWp	2,7	5,5		5,5	5,5	5,5	5,5	5,5	5,5		5,5	5,5
System size m^2	18	32		32	32	32	32	32	32		32	32
Irradiation kWh/m^/year	1122,46	1122,46		1122,46	1284,05	1071,5	1063,21	1111,88	979,07		1122,46	1122,46
Output according to irradiation kWh/kWp	883,81	883,81		883,81	1024,66	836,05	857,28	872,18	768,97		883,81	883,81
Electricity output in the beginning kWh	2386,287	4860,955		4860,955	5635,63	4598,275	4715,04	4796,99	4229,335		4860,955	4860,955
Output decrease %/year	-0,5 %	-0,5 %		-0,5 %	-0,5 %	-0,5 %	-0,5 %	-0,5 %	-0,5 %		-0,5 %	-0,5 %
Share of excess electricity produced %	5 %	5 %		25 %	25 %	20 %	20 %	20 %	15 %		25 %	25 %
Price that excess electricity is sold snt/kWh	2	2		2	2	2	2	2	2		2	2
Lifetime of PV system	30	30		30	30	30	30	30	30		30	30
Costs of the PV system												
Investment cost €	6000	7500		7500	7500	7500	7500	7500	7500		7500	7500
Subsidy (household tax refund)	900	900		900	900	900	900	900	900		900	900
Rate of return	3 %	3 %		3 %	3 %	3 %	3 %	3 %	3 %		3 %	3 %
Costs of changing the inveret % of investment	8 %	8 %		8 %	8 %	8 %	8 %	8 %	8 %		8 %	8 %
Maintenance costs	100	100		100	100	100	100	100	100		100	100
Profitability												
Value of production	11 876 €	17 576 €		17 576 €	20 377,36 €	17 722,81 €	18 172,85 €	18 488,70 €	17 309,19 €		21 140 €	16 248 €
Total costs of the system	9 480 €	11 100 €		11 100 €	11 100,00 €	11 100,00 €	11 100,00 €	11 100,00 €	11 100,00 €		11 100 €	11 100 €
NPV	- 733 €	- 398 €		- 398 €	1 065,28 €	- 321,31 €	- 86,23 €	78,75 €	- 537,36 €		1 464 €	- 1 092 €
IRR %	2,10 %	2,53 %		2,53 %	4,18 %	2,62 %	2,90 %	3,09 %	2,37 %		4,61 %	1,68 %
Payback time (years)	>30	25		25	21	26	25	24	26		20	25
	Change in system size			Change in location							Electricity distribution price changes	

Figure 12:

B Correlations

Table 8: Correlations of model variables

Settlement structure	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Prosumer contracts	1.00													
2. High-rise apartments	−0.07	1.00												
3. Detached houses	0.08	−0.81	1.00											
4. Summer cottages	0.02	−0.71	0.17	1.00										
5. Mean area of a house	0.10	−0.59	0.60	0.28	1.00									
6. Owner-occupied apartments	0.07	−0.87	0.83	0.47	0.72	1.00								
7. Rented apartments	−0.04	0.92	−0.84	-0.55	−0.69	-0.98	1.00							
Socio-demographics														
8. Mean living density	0.27	−0.61	0.38	0.57	0.55	0.62	−0.61	1.00						
9. Highest income class	0.13	0.19	−0.11	-0.19	0.03	-0.11	0.11	-0.31	1.00					
10. Graduate degree	0.08	0.72	−0.60	-0.50	−0.34	-0.72	0.75	-0.59	0.29	1.00				
11. Elementary school	−0.18	−0.56	0.41	0.45	0.34	0.65	−0.67	0.48	0.06	-0.72	1.00			
12. Mean age	0.14	−0.51	0.14	0.70	0.06	0.32	−0.38	0.75	−0.36	-0.55	0.42	1.00		
Irradition & capacity														
13. Mean irradiation	−0.01	0.15	0.11	-0.40	0.25	0.10	−0.03	-0.22	0.13	0.18	0.01	-0.58	1.00	
14. PV capacity	0.81	0.08	0.00	-0.14	0.04	-0.02	0.05	0.02	−0.26	0.17	−0.12	-0.09	0.07	1.00

Correlations of model variables over the years 2013-2018

Table 9: Correlations of model variables

Settlement structure	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. PV capacity	1.00													
2. High-rise apartments	0.51	1.00												
3. Detached houses	−0.40	−0.81	1.00											
4. Summer cottages	−0.38	−0.72	0.17	1.00										
5. Mean area of a house	−0.28	−0.60	0.60	0.28	1.00									
6. Owner-occupied apartments	−0.44	−0.87	0.83	0.47	0.72	1.00								
7. Rented apartments	0.47	0.92	−0.84	-0.55	−0.69	-0.98	1.00							
Socio-demographics														
8. Mean living density	−0.35	−0.65	0.44	0.58	0.59	0.67	−0.67	1.00						
9. Highest income class	0.34	0.42	−0.28	-0.38	0.01	-0.31	0.34	-0.42	1.00					
10. Graduate degree	0.45	0.72	−0.60	-0.50	−0.34	-0.72	0.75	-0.59	0.29	1.00				
11. Elementary school	−0.32	−0.56	0.42	0.44	0.39	0.66	−0.67	0.58	−0.32	-0.69	1.00			
12. Mean age	−0.33	−0.54	0.17	0.70	0.09	0.35	−0.41	0.75	−0.59	-0.58	0.45	1.00		
Irradition & prosumer contracts														
13. Mean irradiation	0.09	0.15	0.11	-0.40	0.25	0.10	−0.03	-0.22	0.35	0.18	0.01	-0.58	1.00	
14. Prosumer contracts	0.21	−0.13	0.17	0.02	0.12	0.16	−0.13	0.21	−0.26	0.17	0.10	0.07	−0.01	1.00

Correlations between model variables over the years 2016-2018