Optimal dimensioning of a solar PV plant with measured electrical load curves in Finland

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Abstract

The amount of installed solar power in Finland tripled in 2016, reaching 27 MWp. In Finland there are no feed-in tariffs, and with the low price of electricity together with the annual distribution of insolation concentrating on summer, the photovoltaic electricity production is economical only when used for self-consumption. When the produced electricity is used for self-consumption, optimization of the photovoltaic power system size is essential for the profitability of the investment. Usually when optimizing the size of the PV system, the electricity production is optimized so that the electricity sold to the grid is minimized. However, this can lead to undersizing of the PV power system. The PV power system size can for example be dimensioned by using methods such as the minimum energy consumption of the building, the maximum power consumption, or the net zero principle. In Finland, the smart meters provide hourly consumption data from the electricity consumers, which can be used to generate electrical load profiles. These smart meters have been installed on almost every real estate.

In this paper, the profitability of a photovoltaic power system in the conditions of southern Finland is studied, simulated, and analyzed for self-consumption. Three cases, a grocery store, a dairy farm, and a domestic house with direct electric space heating, are presented and used in the simulation. Their electricity consumption is measured by hourly automatic meter reading (AMR) on a yearly basis. An Excel tool was used for the analysis of the electrical load profiles against the PV power system production at different system sizes. The profitability of the PV power system was studied by using internal interest rate, net present value, discounted payback period, and self-consumption rate. The effects of government subsidies on the profitability of a PV power system were also examined.

The optimized system sizes for the grocery store, dairy farm, and domestic house with direct electric space heating were 89 kWp, 28 kWp, and 5.2 kWp, respectively. The solar modules of the grocery store and the domestic house were facing south whereas the optimal module orientation in the dairy farm was 50–50% east-west. It was found that in the case of the grocery store and the dairy farm, the PV system size could be increased without the internal rate of return decreasing significantly, and thus, a larger system could be justified. Using the self-consumption ratio to optimize the PV power system size leads to undersizing of the system. It was found that the subsidies for the PV power systems have a significant impact on profitability. In the cases of optimized sizes, the grocery store would be economically viable even if the electricity price decreased annually by 3.6% with subsidies and 1.0% without subsidies. The optimized PV power system of the dairy farm would be economically viable if the electricity price decreased by 3.3% annually; however, without subsidies the electricity price would have to increase by 1.0% annually to remain viable. Considering a residential house, the annual increase in electricity price should be 0.6% with subsidies and 1.9% without subsidies.

Keywords: Photovoltaic power system, Optimization, Dimensioning, Profitability, PV, Nordic conditions

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1. Introduction

The use of photovoltaic (PV) power in the world continues to grow, with the global capacity reaching 303 GWp at the end of 2016 (IEA-PVPS, 2017). The installed capacity in 2016 reached 75 GWp with 35 GWp installed in China alone. China, America, and India are the top three contributors in the total installed PV capacity, accounting for 50% of the solar PV installed in 2016. In Finland, the cumulative installed grid-connected PV capacity tripled in 2016, reaching 27 MWp (The Energy Authority, 2017). However, this number is still low when compared to the PV potential of residential rooftops in Finland. Lassila et al. (2016) found that the PV capacity that could be implemented on residential rooftops could reach 12 000 MWp. This amount of PV installations could be adapted without a significant challenge for the electricity distribution system. The decreasing PV system prices in recent years are making solar power a more competitive and viable option in the residential and industrial sectors (IEA-PVPS, 2016). In Finland, the current system prices with no value added tax (VAT) are in the range of 1300–2000 €/kW in systems of 10 kWp (Ahola, 2017). Smaller system sizes are intended for residential houses. Larger systems for businesses and industrial buildings have a smaller investment cost per kWp because of the lower relative system costs. This is shown in Fig. 1. While the annual solar electricity production potential of southern Finland is around 850 kWh/kWp, the conditions of solar PV production in Finland vary at an annual level because of long days in summer and short days in winter (Kosonen et al., 2014). This leads to the annual distribution of insolation. However, long summer days with high insolation and relatively low average temperatures increase the potential of PV production, making southern Finland similar to northern Germany, where the annual solar power potential is around 900 kWh/kWp (Kosonen et al., 2014).

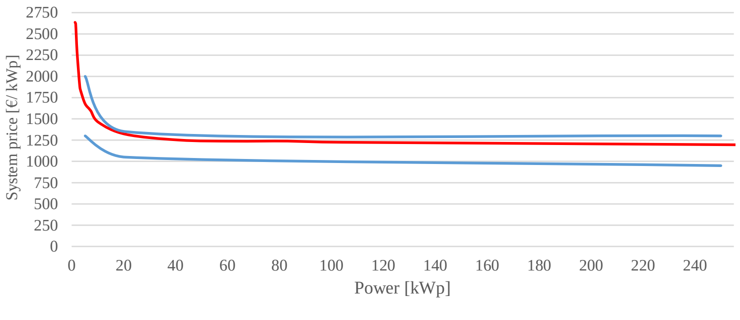

Figure 1: PV system price cost per kWp in Finland with no subsidies. The red line indicates the data used in the example cases, obtained from 2015 (Korhonen, 2016). The blue lines represent estimations of some of the highest and lowest system price costs per kWp in Finland in 2016 (Ahola, 2017).

The PV power system can be sized for example based on the consumers load-profile, profitability, or self-consumption ratio. The self-consumption ratio indicates how much PV power production is used on site and how much is transferred to the grid. The PV power system can be sized by using the consumer's load profile so that the PV power production covers the minimum electricity consumption of the consumer (Mathews et al., 2015). This sizing method provides a high self-consumption ratio, because electricity is rarely sold to the grid. However, the system size varies depending on whether the base load of summer or winter is used when dimensioning a PV power system in the Finnish conditions; this can be seen in Fig. 2. The peak power demand or energy consumption can be used as a basis for the size of the PV power system (Marsan et al., 2015). The PV power system can also be sized based on the net zero concept, where the PV power production within a certain time frame, usually a year, covers the consumption of the building in which it has been installed (Sartori et al., 2012).

Matching the building load to PV production and considering the prices of buying and selling electricity affect the economic profitability of the system (Mondol et al., 2009). However, choosing the size of the PV power system only by optimizing its self-consumption can lead to undersizing and lower profitability of the system. This is because a larger PV power system has lower investment costs per kWp, or alternatively, a lower levelized cost of energy (LCOE) than a smaller system, as can be seen in Fig. 1. A larger system can produce more electricity for the self-consumption of the intended location than a smaller system, meaning less need to buy electricity from the grid. The PV system lifetime is considered to be 20–30 years, and a larger PV system could be chosen to anticipate a possible increase in the electricity consumption in the future. To improve the self-consumption and load matching of a sufficiently sized PV system, a battery energy storage system can be used to store excess energy produced during the day. Applying adjustable loads such as tank-type water heaters during peak production can also be used to increase self-consumption. The stored energy can then be used during periods of high demand or low production. While the price of battery storages is still high, implementing a battery storage to a PV system could be viable in the near future (Muenzel et al., 2015). Using a battery storage by participating in the electricity market as a frequency reserve or balancing power in residential houses could also be a viable option (Belonogova et al., 2016).

The objective of this paper is to use electrical load profiles with 1-hour resolution and simulated grid-connected PV electricity generation to study the profitability of PV power systems for the example cases. Hourly electrical load curves and weather data from the city of Mikkeli in southern Finland were used in the simulation. A sensitivity analysis was performed on the profitability factors. Important factors that affect the profitability are solar yield, system design versus electricity consumption, investment costs, maintenance costs, cost of capital, and the price of electricity. In the calculations of this paper, the Excel tool developed by Korhonen (2016) was applied.

The outline of this article is as follows. First, automatic meter reading (AMR) is introduced and its opportunities and uses are presented. Then, the electricity retail prices in Europe and in Finland are presented together with the subsidies provided for PV systems in Finland. Next, optimization of the PV system is introduced and simulated, and the results are analyzed and discussed. Finally, conclusions are provided.

2. Solar PV policies and smart metering

2.1. Automatic meter reading

All of the cases studied in this paper are equipped with a smart meter, which is used to read hourly energy consumption data of the customer. The EU requires its member states to implement smart metering for the benefit of consumers by 2020 (European Commission, 2014). Finnish legislation provides that the DSOs have smart meters installed for at least 80% of their customers by the end of 2013 (Stephen et al., 2014). Currently, practically all the AMR devices installed in Finland are smart meters. The data provided by AMR can be used to estimate the distribution network state and predict customer behavior (Mutanen et al., 2013). Changes in the customer consumption behavior can be detected by the DSO, and demand response actions can be focused on a specific location and time of day more accurately (Chen et al., 2015). The AMR can also be used in near real-time fault indication and management of low-voltage networks (Stephen et al., 2014). Faults, such as blown fuses and voltage drops can be located using the AMR monitoring information and the distribution management system (DSM) model. It is also possible to measure for instance voltage and current variations, voltage unbalance between phases, and frequency of the supply voltage by AMR. This enables the DSOs to use AMR in power quality monitoring (Järventausta et al., 2010). Fig. 2 shows an example of a monthly load profile based on AMR measurements.

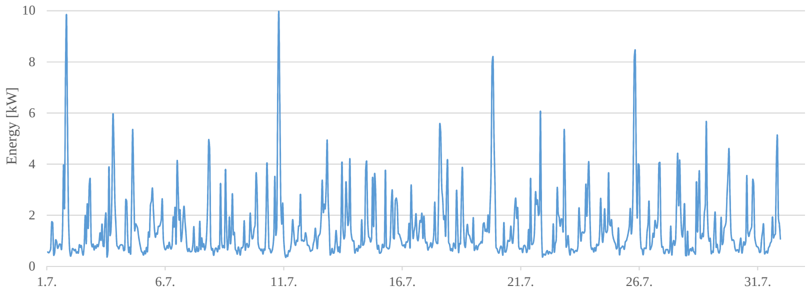

Figure 2: Load profile from July of a typical Finnish domestic house with direct electric space heating. The annual energy consumption is 33 MWh.

Automatic meter reading allows the use of net metering, in which the consumer's energy consumption and production are measured over a predetermined time period (Hirvonen et al., 2015). The difference is calculated for each period and the electricity bill is determined based on the net energy consumption. Further, a legislative initiative for hourly net metering is being processed, in which the electricity being fed to the grid would be net metered and the consumer would be compensated for the energy supplied, networking costs, and taxes (Karimäki, 2017). The AMR data enable the customers to access their consumption profiles and history, which can be used in shifting consumption from peak demand and high electricity prices, thereby resulting in energy savings. Customers with distributed energy production can participate in demand response and network load management (European Commission, 2012, 2011).

2.2. *Price of electricity*

In Finland, the retail price of electricity consists of electric energy, distribution costs, and taxation. The taxes include electricity tax and value added tax. The selling price of PV-produced electricity covers only the electric energy for the consumer, making the price of purchased electricity approximately three times as high as the sold electrical energy, because of taxes and transmission costs. Because selling electricity delivers a lower economic benefit than self-consumption of the produced electricity, increasing the self-consumption ratio can increase the profitability of the PV power system. The electricity retail price in Finland is around 0.15 €/kWh, which is relatively low when compared with other European countries, as can be seen in Fig. 3. The other Nordic countries, such as Sweden and Iceland, also have a relatively low electricity price, excluding Denmark, which had the highest electricity price of the EU member states in 2016.

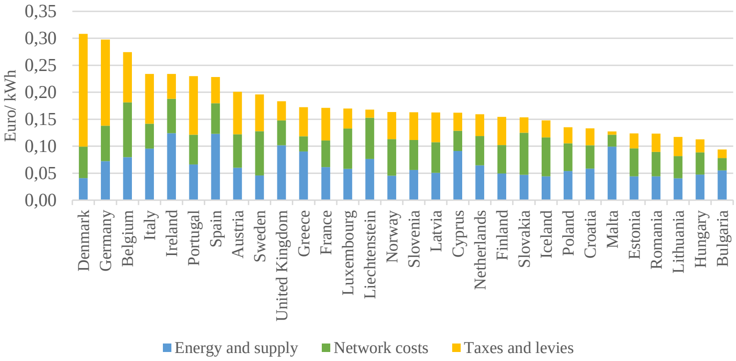

Figure 3: Breakdown of electricity prices for household consumers in Europe, 2016 (Eurostat European Commission, 2017a,b).

Fig. 3 shows how the electricity distribution fees affected the electricity price in 2016. In Finland, the network costs account for more than 50% of the electricity price excluding taxes. This applies also to the other Nordic countries, with the network costs in Sweden being over 60% of the electricity price excluding taxes.

Because of the low electricity price in Finland, without subsidies, the payback period of a residential PV power system remained usually longer than 40 years as was shown in (Hirvonen et al., 2015) in 2015. However, the PV system prices have decreased in Finland (Etelä-Savon Energia, 2017; Finnwind, 2016; Arevasolar, 2017; Ahola, 2017).

2.3. Government subsidies for PV installations

The Finnish Government provides different subsidies to companies and citizens for installing and using renewable energy sources (IEA-PVPS, 2016; Ahola, 2017). For municipalities and businesses, the Government grants a 25% subsidy of the approved investment costs for projects using conventional PV power. Farms are eligible for building investment subsidy from the Government for energy production projects that use renewable energy sources. This subsidy covers only the part of energy production that is used for agricultural production. The granted aid is 40% of the approved investment costs of the energy production project. Households can be granted a tax credit for the total work costs of the PV power system installation. This amount is 45% of their income that falls under value added taxation, up to 2400 euros. The tax credit can range from about 15.6% to 9.5% of the total investment costs in PV power systems smaller than 10 kWp when calculated with the Excel tool used in the simulation.

3. Economic profitability analysis

The profitability of the PV power system was assessed using net present value (NPV), internal rate of return (IRR), and discounted payback period. The discounted payback period alone is not reliable enough because it does not take into account the residual value or the lifetime of the system. However, it can be used to compare different PV investments.

Net present value can be calculated as follows:

$$NPV = \sum_{t=1}^{n} \frac{S_t}{(1+i)^t} + \frac{RV_n}{(1+i)^n} - I_t \tag{1}$$

where S_t is the cash flow of the system in year t, i the interest rate, t the time, RV_n the residual value, n the operating life time of the PV power system, and I_t the cost of the investment. If the net present value is positive, the investment is financially viable.

The internal rate of return is used to estimate the profitability of the investment when the NPV is zero. If the IRR is higher than the reference interest rate, the investment is financially viable. The internal rate of return is given as follows:

$$\sum_{t=1}^{n} \frac{S_t}{(1+r)^t} + \frac{RV_n}{(1+r)^n} - I_t = 0 \tag{2}$$

where r is the internal rate of return and the investment is considered viable when $r \geq i$.

Discounted payback period gives the time in years that is needed for the investment to liquidate the invested capital. The discounted payback period is calculated as follows:

$$\sum_{t=1}^{n^*} \frac{S_t}{(1+i)^t} - I_t = 0 \tag{3}$$

where n^* is the payback time. The investment is considered financially viable if the payback time is lower than the expected lifetime of the investment.

4. Simulation

An Excel-based calculation tool was made to estimate the profitability criteria of the PV power system based on electrical load curves. Three example cases were simulated; a grocery store, a dairy farm, and a residential house with direct electric space heating. The PV power systems were simulated with hourly measured electricity consumption and initial values of the example cases. Initial values are gathered in Table 1. The insolation data used for PV production estimation were provided by the HOMER Pro software, which uses weather and irradiation data gathered by NASA (NASA, 2016). Weather and irradiation data used for the simulation were gathered from the city of Mikkeli, which is located in southern Finland. Data from 2015 were used to calculate the hourly PV production throughout the year, and the year 2015 was used as the reference year. This annual production was used as an estimation over the lifetime of the PV power system. The PV power production calculations were based on ideal production of the PV power system given by the weather data from 2015. For the simulation, the production figures of January, February, and December were ignored due to potential losses caused by snow. Because of the low insolation, the electricity production during these months accounted only for about 2.7% of the annual electricity production (Kosonen et al., 2014). Shading losses were assumed to be minimal in the simulation. The annual module efficiency decrease of 0.5% was taken into account.

The lifetime cycle for the PV modules was set at 30 years and the maintenance costs included replacing the inverter once during the operating lifetime of the system. The electricity spot prices from 2015 were provided by a local energy company, and they were based on the Finnish area price and margin from Nord Pool (Nordpool, 2017). The electricity price for the example

Table 1: Initial values for the PV power system simulation.

Initial values	**Households**	**Businesses (dairy farm, grocery store)**
Price of electrical energy, (margin 2015)	0.3 c/ kWh (24 % VAT)	0.24 c/kWh (0 % VAT)
price of electricity	spot price	spot price
Electricity distribution costs	2.85 c/ kWh (24% VAT)	2.30 c/kWh (0% VAT)
Electricity selling price, (margin 2015)	0.24 c/kWh (0% VAT)	0.24 c/kWh (0% VAT)
Electricity tax	2.79372 c/kWh (24% VAT)	2.253 c/kWh (0% VAT)
Electricity contract fixed charge (€ / month)	3.99	3.22
Electricity transmission fixed charge (€ / month)	7.5	6.05
Interest rate	1%	2%
Annual maintenance costs, (-% of the investment)	0.3%	0.5%
Annual change in electricity price	1.0%	1.0%
System lifetime	30 years	30 years
Annual module efficiency decrease	0.5%	0.5%
Inverter efficiency	98.5%	98.5%
Investment aid	9.5–15.6%	25–40%
Cost of Investment	(24% VAT)	(0% VAT)

cases consists of a fixed electricity contract charge, fixed electricity transmission charge, hourly energy consumption costs, distribution costs, and electricity tax. The fixed charges are monthly and amount to 4.06%, 1.06% and 0.29% of the domestic houses, dairy farms and grocery stores annual electricity costs, respectively. These fixed charges may vary depending on the electricity supplier and the negotiated contracts, which can result in variations on the electricity prices (Eurostat European Commission, 2017a). Based on the measurement of hourly consumption and production, the customer either pays or sells electricity depending on whether the production exceeds consumption within an hour interval. The investment costs for the PV power system were provided by the manufacturers and retailers, and can be seen in Fig. 1. The PV system prices of 2015 were used in the simulation. In the cases of the grocery store and the dairy farm, the PV power system prices did not include VAT. For the residential house, the VAT of 24% was included in the PV power system costs. The government subsidies for the example cases were included in the investment costs. The PV power system can be considered a low-risk investment because of the predictability of the income. The interest rate of 1% was chosen because it is higher than the available average interest rate for a savings account deposit in 2018, which is 0.425% (Kauppalehti, 2018). For the grocery store and the dairy farm, an interest rate of 2% was chosen to match the inflation target of the next few years. For the residential household it was assumed that part of the maintenance could be performed by the resident, and thus, a lower annual cost was chosen.

The tool returns NPV, IRR, and discounted payback period as a function of PV power. An investment sensitivity analysis was used, where the effects of investment costs, maintenance costs, current price of electricity, and the annual changes in electricity price and interest rate on the NPV of the investment were studied.

4.1. Grocery store

A grocery store with an annual energy consumption of 485 MWh was studied for PV power system installation. The grocery store is located in southern Finland, and its monthly energy consumption from 2015 is shown in Fig. 4. Because of the constant need for cooling and lighting, the monthly electricity consumption for the grocery store remains relatively stable throughout the year. However, in summer, more cooling is required because of the warmer temperatures. The

PV modules are facing south and their inclination is set to 30°. The investment aid granted for the project is 25% of the investment costs.

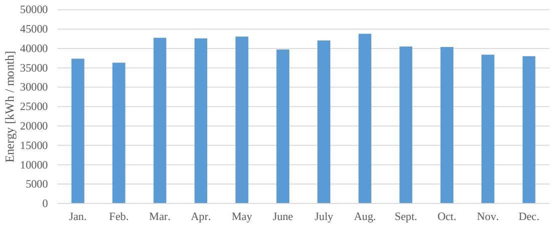

Figure 4: Energy consumption of the grocery store in 2015.

The IRR and NPV were calculated for the PV power system at different system sizes. The discounted payback period and self-consumption ratio were also considered in the profitability estimation. The IRR gave an optimal system size of 89 kWp with a 6.8% profit. Using the NPV, the optimal system size was 250 kWp. The calculations of the profitability method are shown in Fig. 5.

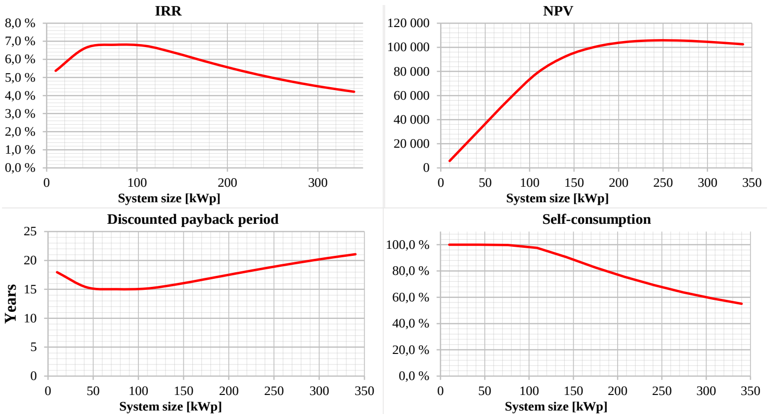

Figure 5: PV power system sizing for the grocery store. South-facing system presented with internal rate of return and net present value.

For a comparison, the system size of 89 kWp was doubled and the profitability calculated using IRR and NPV. The results of the profitability methods for the chosen system sizes are gathered in Table 2. The discounted payback period does not increase significantly when the system size is increased from 89 kWp to 250 kWp. The larger system size also covers more of the overall consumption of the building. However, the self-consumption ratio decreases as the PV power system size is increased, meaning that more electricity is sold to the grid.

The IRR decreases only from 6.8% to 5.0% when increasing the system size from 89 kWp to 250 kWp. The difference in the NPV when increasing the system size from 178 kWp to 250 kWp is slight. Fig. 6 presents the production and consumption of the grocery store in an average day in June and October.

In June, when the irradiation is high, the larger PV system produces more than the average

Table 2: Results of the profitability methods for the grocery store, with subsidies.

PV power system size	**89 kWp**	**178 kWp**	**250 kWp**
Cost of investment, subsidized (€)	82 172	161 946	225 172
Subsidy portion of total cost (%)	25	25	25
Internal rate of return (%)	6.8	5.9	5.0
Net present value (€)	66 068	101 098	105 842
Self-consumption (%)	99.5	82.0	67.7
PV electricity of total consumption (%)	16.4	27.0	31.3
Discounted payback period (years)	15.0	16.9	18.9

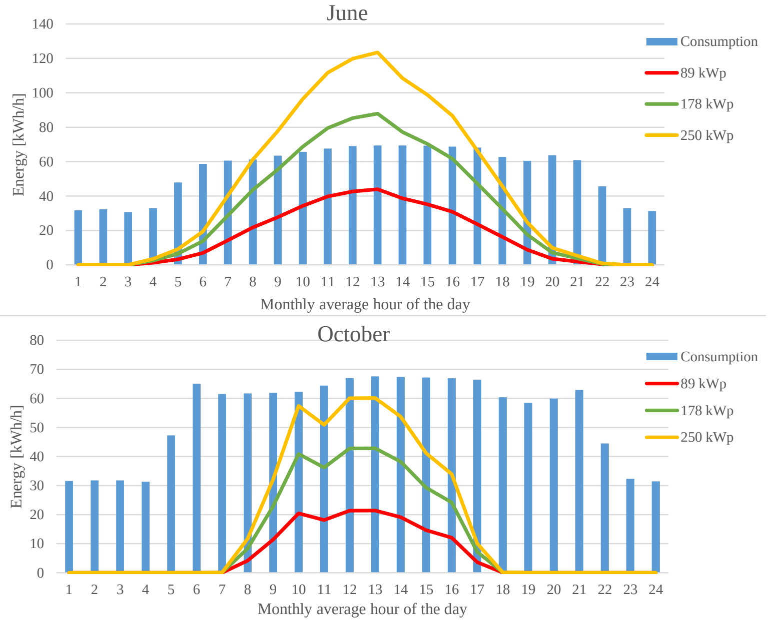

Figure 6: Production and consumption of the grocery store in an average day in June and October.

consumption at peak hours, and electricity is sold to the grid. In October when the irradiation is lower, even the largest PV system does not produce enough to cover the consumption on average. The NPV of the investment costs was studied with and without investment aid and is presented in Fig. 7.

The 89 kWp system is viable with the 25% investment aid even if the price of electricity decreases by 3.6% annually. Without the investment aid, the electricity price could decrease by 1% annually, and the system size would remain viable. Even if the price of electricity decreases by 1.7% annually, the 250 kWp system would remain economically viable with the investment aid. Without the investment aid, the electricity price would have to increase by 0.6% annually for the system to be viable.

A sensitivity analysis was calculated for the 89 kWp and 250 kWp system sizes. The most sensitive factors were found to be the cost of investment and the current price of electricity. The 89 kWp system size would remain viable if the costs of investment increased by 72%. For the 250 kWp system, the investment costs could increase by 42% and remain viable based on the

Figure 7: Effects of investment aids on the NPV investment costs of the PV power system as a function of electricity price change for the grocery store.

NPV. The current electricity price could decrease by 42% for the 89 kWp system and it would be viable based on the NPV. For the 250 kWp system, the electricity price could decrease by 30% and remain viable based on the NPV. Because the NPV does not increase significantly when increasing the system size from 178 kWp to 250 kWp, it might not be viable because of the increased risks in investing. However, choosing the PV power system size based on the self-consumption leads to a small system, which would not cover even the base load in the summer. The most profitable PV power system size for the grocery store, given by the IRR, is 89 kWp.

4.2. Dairy farm

A farm located in southern Finland with annual electrical consumption of 133 MWh was examined for PV system installation. While facing the solar modules south is a rule of thumb to provide the best annual production, the peak consumption of the farm occurs in the mornings and evenings owing to milking of cows and cooling of the milk. Rhodes et al. (2014) studied the effects of PV array orientation on the energy production and value and found that in some cases the optimal orientation was partly (20–51° west of south and 10–20° east of south) to the west or to the east when considering the economic value of the produced energy. They also showed that increasing the module angle when the modules are directed towards east or west, decreased the amount of annual energy yield. Even if Finland locates above 60° latitude and Austin mentioned in Rhodes et al. at 30° latitude, the effect of module angle change is similar with east and west installation. In Finland, best annual yield is received with 0° with east and west installation and the yield decreases when the module angle increases. At the same time, peak production moment shifts towards morning (east installation) or evening (west installation), when the module angle increases.

To match the production and consumption of the dairy farm, the modules were divided so that 50% were facing east and 50% west to increase the production in the mornings and evenings. The angle of the modules was set to 20° according to the roof angle. A PV system with modules facing south was used as a reference. The farm can receive government support to cover 40% of the investment costs. The monthly energy consumption of the farm for 2015 is shown in Fig. 8.

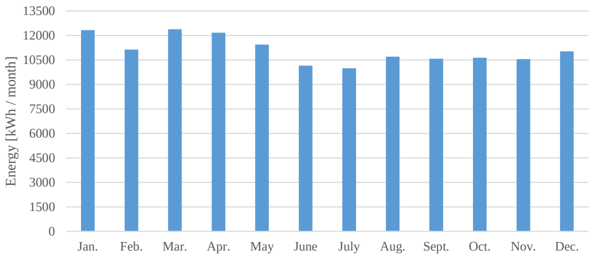

Figure 8: Annual energy consumption of the farm in 2015.

The profitability and size of the PV power system for the farm was studied with NPV and IRR. The discounted payback period and self-consumption ratio was also calculated. A PV system with all modules facing south was calculated for comparison. The results are presented in Fig. 9. The optimal size was found to be 28 and 76 kWp when using IRR and NPV, respectively, for the east-west configuration. The optimized south configuration gave PV system sizes of 23 and 96 kWp when using IRR and NPV, respectively. According to the results, south installation is still better than the east-west one from the profitability point of view, even if the consumption profile is weighted to morning and evening in this case. The best installation angle is always the roof angle, because of the costs and shadowing effects. On the other hand, larger angles were simulated with east-west installation case to see the behavior of profitability. According to these, larger angles do not increase the profitability factors compared to 20° installation angle in this case.

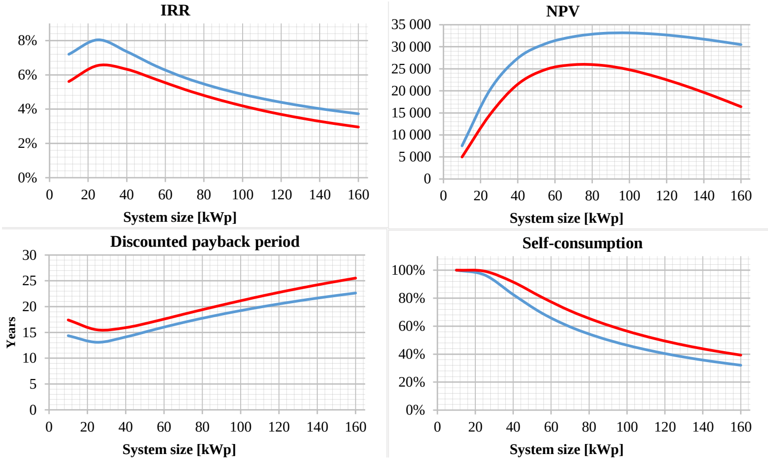

Figure 9: PV power system sizing for the dairy farm. The east-west (red) and south (blue) configurations presented with internal rate of return and net present value.

The IRR was 6.6% for the 28 kWp east-west configuration and 8.1% for the 23 kWp south configuration PV system. The discounted payback period was found to be 15.5 years for the east-west configuration and 13.1 for the south configuration. The results are given in Table 3. For comparison, the 28 kWp system was doubled and analyzed by the IRR and NPV methods.

Table 3: Results of the profitability methods for the dairy farm, with subsidies.

PV power system size	**28 kWp, east-west**	**56 kWp, east-west**	**76 kWp, east-west**	**23 kWp, south**
Cost of investment, subsidized (€)	21 615	41 876	56 344	17 999
Subsidy portion of total cost (%)	40	40	40	40
Internal rate of return (%)	6.6	5.7	4.9	8.1
Net present value (€)	16 311	24 975	26 004	18 777
Self-consumption (%)	98.3	80.0	67.6	97.8
PV electricity of total consumption (%)	15.4	25.0	28.7	14.6
Discounted payback period (years)	15.5	17.2	19.1	13.1

Increasing the PV system size increases the proportion of electricity that the PV system provides of the overall consumption. However, it decreases the self-consumption ratio of the PV system. Increasing the PV system size also extends the discounted payback period, while remaining below the PV system lifetime. The IRR is not significantly affected by the increased PV system size. Based on this criterion, it could be viable to choose a larger PV system. The NPV is not significantly affected by the increase in the system size from 56 kWp to 76 kWp, which leads to a conclusion that the risks of investment increase more than the profits when increasing the PV system size.

When observing the consumption and production of an average day in June, the east-west configuration produces more electricity during the morning and evening periods than the south configuration (Rhodes et al., 2014). However, in spring and fall when the Suns declination changes, the east-west configuration produces less electricity on average than the south configuration. This can be seen in Fig. 10.

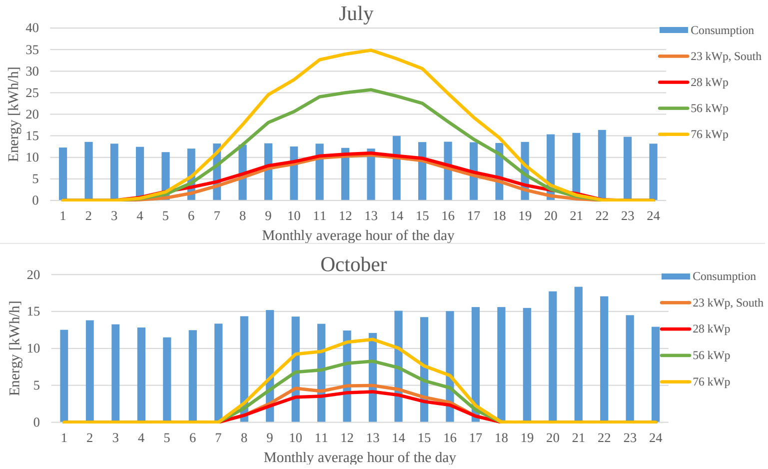

Figure 10: Production and consumption of the farm in an average day in July and October. East-west and south configurations.

In summer, the electricity production of the 56 kWp and 76 kWp systems exceeds the consumer's load, and thus, the surplus will be sold to the DSO. In October, all the studied systems produce enough electricity to cover the consumption on average, and hence, no electricity is sold to the grid. Fig. 11 shows the NPV investment costs as a function of electricity price change. The effects of investment support are also shown.

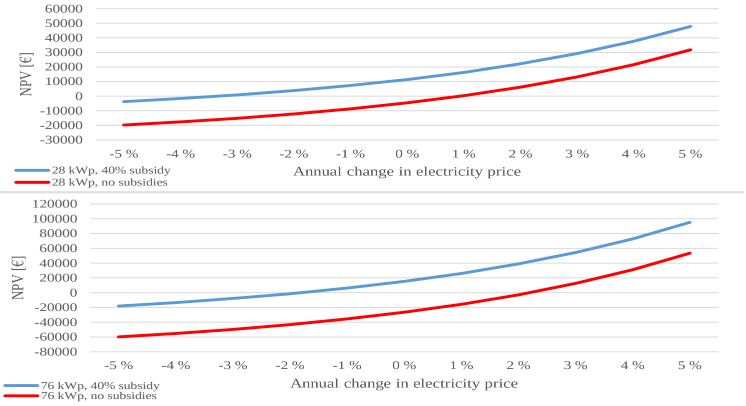

Figure 11: Effects of investment aids on the NPV investment costs of the PV power system as a function of electricity price change for the farm.

The 28 kWp system with investment support of 40% would remain viable even if the price of electricity decreased 3.3% annually throughout its lifetime. Without investment aid, the price of electricity would have to increase by 1% annually for it to remain viable. The 76 kWp system with investment support would be economically viable even with an electricity price decrease of 1.6% annually, while without investment aid the price would have to increase by 2.2% annually to remain economically viable.

The sensitivity analysis of the investments revealed that the most sensitive factors for the farm were the investment costs and the price of electricity. For the 28 kWp PV system, the investment costs could rise by 68% and the system would still remain economically viable. With the 76 kWp system, the increase could be 42%. The price of electricity can be 40% lower for the 28 kWp system and 29% lower for the 76 kWp system, the investment still remaining economically viable. The IRR method provides the most profitable PV power system size, which is 28 kWp.

4.3. Domestic house with direct electric space heating

A house with electric heating was studied for the PV power system investment. The annual consumption was 33 MWh and the house was located in southern Finland. The modules were facing south and installed at a 20° angle. The domestic house receives a tax credit as an investment support. The monthly energy consumption of a domestic house for 2015 is shown in Fig. 12. It can be seen that the electricity consumption in winter can be about five times as high as the electricity consumption in summer, while the PV production is small in winter and high in summer. Consequently, optimization of the PV power system size is highly important for domestic houses.

The simulation results are presented in Fig. 13. With IRR and NPV, the optimal system size was 5.2 kWp and 6.0 kWp, respectively. Because of the similar results, the zero value IRR and the close to zero NPV were chosen for comparison for the IRR optimal value. The PV system size of 1.3 kWp with almost 100% self-consumption was also included in the analysis.

The zero value for IRR is 19.1 kWp and 10 kWp for NPV. The results of the profitability methods are gathered in Table 4. The proportion of investment costs compensated for by tax

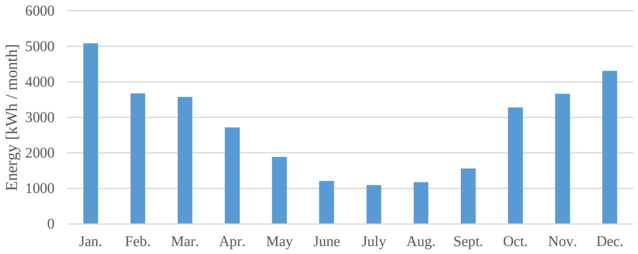

Figure 12: Annual energy consumption of a domestic house with electric space heating in 2015.

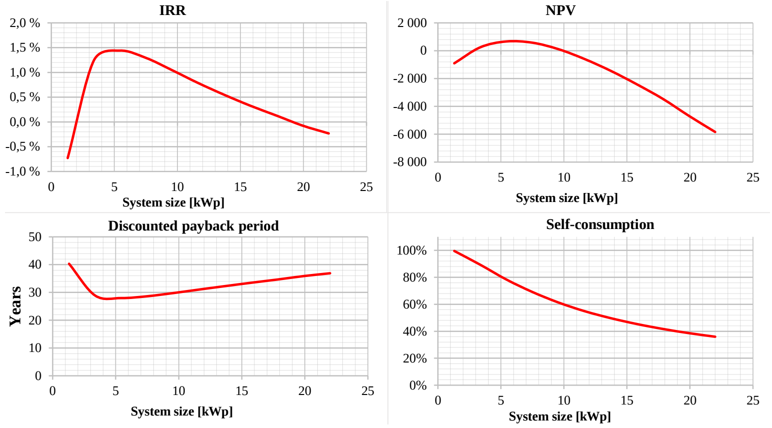

Figure 13: PV power system sizing for a domestic house with electric heating presented with internal rate of return and net present value.

credits decreases as the system size increases; with the 5.2 kWp system it is 11.4% and with the 19.1 kWp system 7.4%.

Table 4: Results of the profitability methods for the house with electric heating, with subsidies.

PV power system size	**1.3 kWp**	**5.2 kWp**	**10.0 kWp**	**19.1 kWp**
Cost of investment, subsidized (€)	3 787	9 553	16 488	29 425
Subsidy portion of total cost (%)	15.6	11.4	9.6	7.4
Internal rate of return (%)	–0.7	1.4	1.0	0.0
Net present value (€)	–904	647	–22	–4 234
Self-consumption (%)	99.5	79.5	59.9	39.8
PV electricity of total consumption (%)	3.4	10.8	15.6	19.8
Discounted payback period (years)	40.3	28.0	30.0	35.5

The self-consumption ratio is the lower, the larger is the system size. This is explained by the fact that the peak production occurs in summer when the consumption is low, and consequently, excess electricity is sold to the grid. This can be seen in Fig. 14. The larger system size, however, increases the investment cost, and the discounted payback period of the 19.1 kWp system is longer than the estimated system lifetime. This is also the case with the 1.3 kWp system size. While the 1.3 kWp has the highest self-consumption, it is the least profitable PV system size with the -0.7% IRR and a discounted payback period that exceeds the expected lifetime of the system.

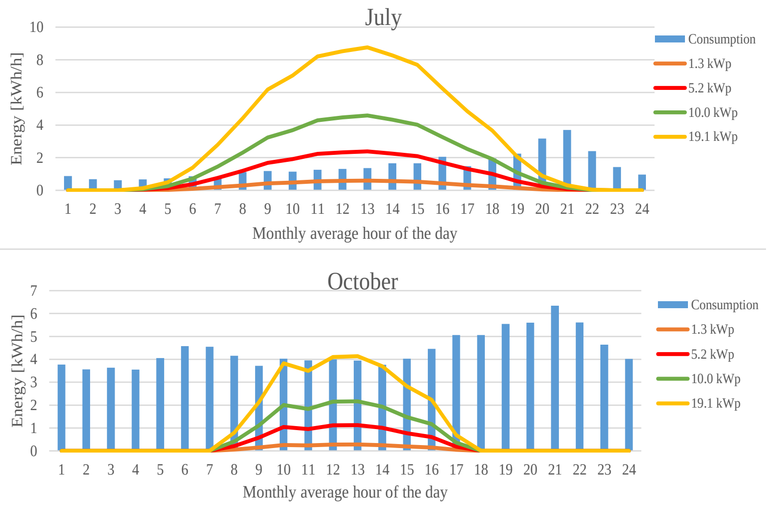

Figure 14: Production and consumption of a residential house with electric heating in an average day in July and October.

In summer, the peak load occurs in the evening, whereas the peak production takes place during the day. In October, only the production of the 19.1 kWp system exceeds the load on average, and electricity is sold to the grid. In Fig. 15, the NPV of the investment is presented as a function of electricity price change with and without tax credit.

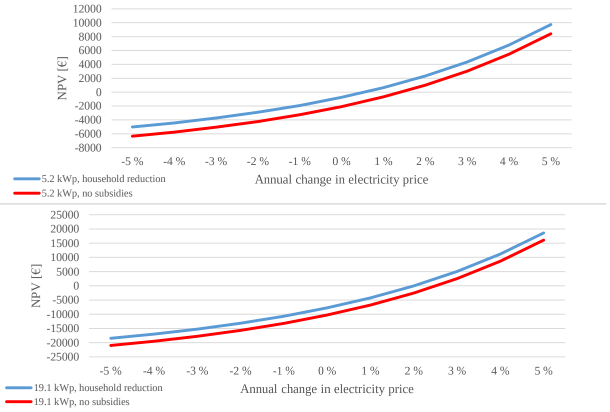

Figure 15: Effects of investment support on the NPV investment costs of the PV power system of a residential house with electric heating as a function of electricity price change.

The 5.2 kWp system would require the electricity price to rise by 0.6% annually for the NPV to remain viable with tax credit. Without tax credit, the prices would have to rise by 1.9% annually. The NPV of the 19.1 kWp system with tax credit would remain economically viable if the electricity prices increased by 2.5% annually. Without tax credit, the electricity prices would require a 3% annual increase for the 19.1 kWp system to remain economically viable.

In the household case, the most sensitive factors for the NPV of the investment were the price of electricity and investment costs. However, the 5.2 kWp system was more sensitive to the current electricity price, and the NPV of the 19.1 kWp system was more sensitive to the investment costs. If the current electricity price increased by 18% or the cost of investment decreases by 14%, the 19.1 kWp system would become economically viable. The most profitable and economically viable PV power system size for the house with electric heating is 5.2 kWp, which is given by the IRR method. With the current price of electricity, a larger system size is not viable.

5. Results and discussion

In this study, the profitability of PV power systems for self-consumption was assessed with internal rate of return and net present value for three cases (grocery store, dairy farm, and domestic house) in Finland. The results for the optimized PV system sizes are given in Table 5. For the chosen cases, the IRR method provided the most profitable system size when the government subsidies were considered. The IRRs were 6.8%, 6.6%, and 1.4% for the grocery store, dairy farm, and residential house, respectively. The results obtained in the cases of the grocery store and the dairy farm can be further applied to other buildings with a similar electrical consumption profile. For the residential house with direct residential heating, the load profile of the house may have an effect on whether the results can be applied to other cases or not. However, the NPV showed that in the case of the grocery store or the farm, a significant increase in the PV system size would not make the investment unprofitable. While electricity is sometimes sold to the grid even with the optimized system sizes, the self-consumption rate is high for the systems with 99.5%, 98.3%, and 79.5% for the grocery store, farm, and residential house, respectively. Larger PV systems had a lower self-consumption rate and the amount of electricity sold to the grid was increased. This is affected by seasonal differences in insolation in Finland. In summer, the high insolation produces more electricity, and on average, electricity is sold daily to the grid with larger PV system sizes. In spring and autumn, the insolation is lower and the produced electricity is used for self-consumption. This poses a challenge for residential houses as they have a low electricity consumption in summer but a high consumption in autumn, winter, and spring as a result of heating demand in the case of electric space heating. For the grocery store and the farm, which have a relatively stable monthly consumption throughout the year, the PV power system can be optimized by sizing the system according to the electricity consumption in summer when the PV production is at highest. However, optimizing the PV system based on the self-consumption rate can lead to undersizing. This can be observed in the cases of the farm or the grocery store, where choosing a larger system size would still be profitable and the IRR of the investment would not be significantly decreased.

Table 5: Results of the profitability methods and sensitivity analysis.

PV power system size	**Grocery store**	**Farm**	**Domestic house with electric heating**
Annual consumption, MWh	485	133	33
Module direction	South	East-West	South
Module angle	30°	20°	20°
Most profitable system size, kWp	89	28	5.2
Internal rate of return, %	6.8	6.6	1.4
Allowed annual change in electricity price, with subsidies, %	–3.6	–3.3	0.6
Change in estimated investment costs, %	72	68	6

The sensitivity analysis showed that for the grocery store and the farm, the change in the investment costs can increase significantly, the PV system still remaining profitable. This is due to the fact that the investment costs per installed kWp are lower at larger system sizes. The domestic house is more sensitive to an increase in the investment costs, because a small system size has a higher cost of investment per installed kWp. When considering the annual change in the electricity price, the domestic house is more sensitive than the grocery store or the farm. The annual price would have to rise by 0.6% annually with government subsidies, whereas in the case of the grocery store or the farm, the electricity price could decrease annually by 3.6% and 3.3%, respectively. However, a continuing decrease in electricity price does not seem likely. The investment support for domestic households is lower than for companies and agriculture in Finland. This is evident when examining the prices of the domestic houses 19.1 kWp system and dairy farms 23 kWp system. While the dairy farm has almost 4 kWp larger system the price difference is significant with dairy farms PV power system costing 17 999 € and domestic houses PV power system costing 29 425 €. Balancing the subsidies provided by the government could increase the profitability of the PV power system investment for domestic houses.

In addition, the lack of hourly net metering systems has a direct effect only on the consumers in practice. In the future, there could be electrical storage systems, electric cars, and smart load control, which would increase the need for more solar PV production. Profitability could also be increased with demand response by matching the PV production and consumption of the consumer.

6. Conclusions

In this paper, the profitability of grid-connected PV installation was studied by example cases located in southern Finland. The production of solar power for self-consumption was examined by the cases of a grocery store, a dairy farm, and a domestic house with direct electric space heating. The weather and insolation data from southern Finland were used to simulate the PV systems in an Excel-based calculating tool. Electrical load profiles were generated using hourly energy consumption measurements. The IRR and the NPV were used to optimize the dimensioning of the PV power system. A sensitivity analysis was carried out for the profitability factors. The optimized PV power system sizes for the grocery store, dairy farm, and domestic house were found to be 89 kWp, 28 kWp, and 5.2 kWp, respectively. The sensitivity analysis showed that for the domestic house the electricity price would have to increase by 0.6% annually for the PV system to be profitable even with the tax credit. For the grocery store, the PV system investment with current 25% investment subsidies would remain profitable if the electricity price decreased by 3.6% annually, whereas for the farm a 3.3% annual decrease would keep the subsidized investment profitable. However, even without the subsidies, the PV power system can be an economically profitable investment in Finland if a high self-consumption ratio is achieved.

It was also found that with the grocery store or the farm increasing the PV power system size does not significantly decrease the IRR of the investment, meaning that a larger system than the proposed optimal PV power system could be chosen without significantly decreasing the profitability of the investment. A larger PV system size can also be used to cover a possible increase in the electricity consumption in the future.

It was found that the self-consumption ratio does not necessarily have to be close to 100% for the investment to remain economically viable. If the PV power system is sized based on a high self-consumption ratio and only the base load of the building is covered, it leads to an undersized system. This can be economically unviable as is evident in the case of the domestic house, where the PV system of 1.3 kWp was the least profitable option. Optimizing the PV power system based on the lowest consumption of an average day in the summer can lead to an unprofitable investment, because the size of the PV power system affects heavily on the system prices per kWp when in the range of smaller than 10 kWp systems. Thus, to avoid undersizing and an economically unviable PV system size, other optimization methods should be used.

With automatic meter reading it is possible to measure the energy consumption of the consumers and generate hourly load profiles. The annual variation in insolation poses a challenge, because production is at highest in summer when the overall consumption is low. This is most evident in domestic houses with direct electric space heating. The consumption peak occurs in winter when the heating demand is at highest and insolation at lowest, providing little PV production. This, together with the low electricity price in Finland, makes the PV system for domestic houses a sensitive investment based on the IRR or a change in the investment costs, even with government subsidies. For buildings with larger monthly consumption, such as the dairy farm and the grocery store, the PV power system is a profitable investment. This is also explained by the fact that business and agricultural buildings are provided with higher government subsidies for PV installations. Increasing the tax credit for domestic house PV installations could help PV integration in Finland.

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References

Ahola, J., 2017. National survey report of pv power applications in finland 2016.

Arevasolar, 2017. Price lists. `http://www.arevasolar.fi/fi/hinnasto`, [Online; accessed: 04-Aug-2017].

Belonogova, N., Haakana, J., Tikka, V., Lassila, J., Partanen, J., 2016. Feasibility studies of end-customer's local energy storage on balancing power market. In: CIRED Workshop. Helsinki, Finland.

Chen, T., Mutanen, A., Järventausta, P., Koivisto, H., June 2015. Feasibility studies of end-customer's local energy storage on balancing power market. In: IEEE Powertech Eindhoven 2015. Eindhoven, Netherlands.

Etelä-Savon Energia, 2017. Aurinkosähköjrjestelmien hinnasto. `https://ese.fi/fi-fi/article/etusivu/aurinkosahkojarjestelmien-hinnasto/54/`, [Online; accessed: 04-Aug-2017].

European Commission, 2011. Definition, expected services, functionalities and benefits of the smart grids. `http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011SC0463&from=EN`, [Online; accessed: 02-Aug-2017].

European Commission, 2012. Recommendation of 9 march 2012 on preparations for the roll-out of smart metering systems. `http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012H0148&from=EN`, [Online; accessed: 02-Aug-2017].

European Commission, 2014. Benchmarking smart metering deployment in the eu-27 with a focus on electricity. `http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0356&from=EN`, [Online; accessed: 30-Oct-2017].

Eurostat European Commission, 2017a. Electricity price statistics. `http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics`, [Online; accessed: 13-Mar-2018].

Eurostat European Commission, 2017b. Electricity prices components for household consumers - annual data (from 2007 onwards). `http://ec.europa.eu/eurostat/web/energy/data/database`, [Online; accessed: 02-Oct-2017].

Finnwind, 2016. Aurinkosähkö - verkkoon kytkettävä. `http://www.verkkokauppa.finnwind.fi/tuotteet.html?id=1/`, [Online; accessed: 04-Aug-2017].

Hirvonen, J., Kayo, G., Cao, S., Hasan, A., Sirén, K., Apr. 2015. Renewable energy production support schemes for residential-scale solar photovoltaic systems in nordic conditions. Energy Policy 79, 72–86.

IEA-PVPS, 2016. Trends in photovoltaic applications 2016. `http://iea-pvps.org/fileadmin/dam/public/report/national/Trends_2016_-_mr.pdf`, [Online; accessed: 30-Oct-2017].

IEA-PVPS, 2017. Press release: International energy agency photovoltaic power system programme (iea pvps) publishes its new 'snapshot of global photovoltaic markets 2016'. `http://www.iea-pvps.org/fileadmin/dam/public/Press_Releases/Press_Release_T1_-_Snapshot.pdf`, [Online; accessed: 02-Aug-2017].

Järventausta, P., Repo, S., Rautiainen, A., Partanen, J., Dec. 2010. Smart grid power system control in distributed generation environment. Annual Reviews in Control 34 (2), 277–286.

Karimäki, J., 2017. Lakialoite laiksi sähkömarkkinalain muuttamisesta. `https://www.eduskunta.fi/FI/vaski/Lakialoite/Sivut/LA_4+2017.aspx`, [Online; accessed: 09-Oct-2017].

Kauppalehti, 2018. Talletuskorko. https://beta.kauppalehti.fi/porssi/korot/talletuskorot, [Online; accessed: 13-Mar-2018].

Korhonen, M., 2016. Optimized photovoltaic power system by electricity load curve and simulated electricity generation. Master's thesis, Lappeenranta University of Technology, Lappeenranta, Finland.

Kosonen, A., Ahola, J., Breyer, C., Aug. 2014. Large scale solar power plant in nordic conditions. In: 16th European Confrence on Power Electronics and Applications (EPE'14-ECCE Europe). Lappeenranta, Finland.

Lassila, J., Tikka, V., Haapaniemi, J., Child, M., Breyer, C., Partanen, J., June 2016. Nationwide photovoltaic hosting capacity in the finnish electricity distribution system. In: 32nd European Photovoltaic Solar Energy Conference and Exhibition. Munich, Germany.

Marsan, M., Bucalo, G., Caro, A. D., Meo, M., Zhang, Y., 2015. Towards zero grid electricity networking: powering bss with renewable energy sources. In: International Conference on Communications Workshops. Budapest, Hungary.

Mathews, N., Rao, N., Gowrisankar, Pattnaik, B., Prasad, G. S., 2015. Grid tied roof top solar: problems, learnings and solutions. In: International Conference on Sustainable Green Buildings and Communities. Chennai, India.

Mondol, J., Yohanis, Y., Norton, B., July-Aug. 2009. Optimising the economic viability of grid-connected photovoltaic systems. Applied Energy 86 (7–8), 985–999.

Muenzel, V., de Hoog, J., Mareels, I., Vishwanath, A., Kalyanaraman, S., Gort, A., 2015. Pv generation and demand: evaluating the potential of residential storage. In: IEEE Innovative Smart Grid Technologies Conference. Washington DC, USA.

Mutanen, A., Järventausta, P., Kärenlampi, M., Juuti, P., 2013. Improving distribution network analysis with new amr-based load profiles. In: 22nd International Conference of Electricity Distribution. Stockholm, Sweden.

NASA, 2016. Surface meteorology and solar energy. https://power.larc.nasa.gov/, [Online; accessed: 16-Nov-2017].

Nordpool, 2017. Elspot prices hourly 2015 eur. http://www.nordpoolspot.com/historical-market-data/, [Online; accessed: 16-Nov-2017].

Rhodes, J., Upshaw, C., Cole, W., Holcomb, C., Webber, M., Oct. 2014. A multi-objective assessment of the effect of solar pv array orientation and tilt on energy production and system economics. Solar Energy 108, 28–40.

Sartori, I., Napolitano, A., Voss, K., May 2012. Net zero energy buildings: a consistent definition framework. Energy and Buildings 48, 220–232.

Stephen, B., Mutanen, A., Galloway, S., Burt, G., Järventausta, P., Feb. 2014. Enchaned load profiling for residential network customers. IEEE Transactions on Power Delivery 29 (1), 88–96.

The Energy Authority, 2017. National report on electricity and natural gas markets in 2016. `https://www.energiavirasto.fi/documents/10191/0/National_Report_2017_Finland_1469-401-2017.pdf/6b783563-e997-4c4c-ace9-826d68447c9b`, [Online; accessed: 02-Aug-2017].