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# Solar Heat Pumps and Self-Consumption
# Can (and should) electricity suppliers encourage thermal storage?

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## Abstract

Heat pumps and water tanks can be used to increase PV self-consumption in buildings without any additional equipment, but there is sometimes a lack of economic incentives to maximize it that limits economic gains. Therefore, pricing conditions need to change in order to make self-consumption strategies more interesting for prosumers. This study aims at determining what, if any, unsubsidized market conditions could lead to economically motivated self-consumption control strategies with solar heat pumps. A sensitivity analysis is used on multiple pricing models based on current market conditions for a solar PV and ground source heat pump system for a single-family house in Norrköping, Sweden. The results show that control strategies aimed at maximizing self-consumption have very little impact on net costs, regardless of pricing model or variation in price. Feed-in-bonus is the most important aspect when comparing different pricing schemes, and no other sensitivity comes close.

## Introduction

Solar photovoltaic installed capacity in Sweden has been growing rapidly during the past 10 to 15 years, going from 14.6 MW in 2011 to 1.1 GW in 2020. Of the 1.1 GW of cumulative installed capacity in 2020 6.6% corresponds to grid-connected centralized systems and 91.9% to grid-connected decentralized systems, with the remaining corresponding to off-grid systems (Lindahl et al., 2021).

Part of the growth of solar PV installations in Sweden, besides the decline in the cost of PV modules, is due to the introduction of direct capital subsidies that have been around since the year 2006. Particularly in the residential sector, it is due to the existence since 2015 of a PV-feed-in bonus for overproduced electricity sold to the grid. The presence of this feed-in-bonus encourages the use of larger systems with lower self-consumption, since the sale price of PV electricity to the network is favourable for prosumers. However, as the installation costs for PV systems continue to decrease, the support programs in place to make it easier or more profitable to install PV systems will also decline. This entails a risk to poor economic outcomes if the feed-in subsidies are removed.

Battery storage is often looked to as the default option for increasing PV self-consumption, and installations are increasing rapidly in many mature markets (Aniello et al., 2021). Another alternative is to exploit the great potential of heat pumps and water tanks without any additional equipment, but there is sometimes a lack of economic incentives to maximize it that limits economic gains (Fischer, 2017). Therefore, pricing conditions need to change in order to make self-consumption strategies more interesting for prosumers.

This study aims at investigating different pricing strategies that would make self-consumption an interesting option for prosumers when designing a solar heat pump (SHP) system.

## Background

The largest part of electricity costs for consumers in Sweden are taxes, followed by electricity trading costs and transmission and distribution costs. According to a report by Energimarknadsinspektionen (Ei), in 2019 taxes accounted for 42.7% of total electricity cost paid by consumers, electricity trading a 34.6% and transmission and distribution a 22.7% (Lusth et al., 2020). The different contracts and associated costs in the Swedish electricity market are presented in the following sections.

### Network costs

Electricity network costs in Sweden are usually comprised of a fixed component and a variable component. The fixed component is a subscription charge, which depends on the fuse capacity for which the customer has subscribed. The variable component, is directly linked to the customer´s electricity consumption and is usually referred to as volumetric price [SEK/kWh] (Lusth et al., 2020). Since the early 2000s, distributed system operators (DSO) have been shifting towards a capacity pricing model to penalize high peak power loads rather than high electricity consumption. Under this model, the top three hourly loads during the peak pricing period, which occurs between 7.00 and 19.00 on weekdays, is averaged to get a peak load. That peak load is then multiplied by a cost per kW that varies between the winter peak period, running from November to March, and the off-peak summer period, that runs from April to October. The off-peak and on-peak prices of one of the utility companies in Sweden, which is taken as a reference for this study, is of 55.75 SEK/kW and 111.50 SEK/kW respectively, while the annual network fixed price is set to 1530 SEK/yr.

**Energy costs**

Trading on the wholesale market in Sweden and the Nordic – Baltic region takes place on the Nord Pool electricity exchange. Under this market, electricity producers get paid per hour according to the electricity that is sold, and not for installed capacity (Lusth et al., 2020).

Electricity retailers then charge customers based on the electricity used. Depending on the type of contract, the retailer will charge a fixed annual fee and a variable or fixed electricity price per kWh. In addition, the customer might have to pay for a supplier fee or green certificates. Electricity prices are based on the Nordpool spot market (Nord Pool Spot, 2019), and the fixed annual fee and supplier fee are taken from one of the electricity retailers operating in Norrköping and set to 330 SEK/yr and 0.050 SEK/kWh (Energimarknadsinspektionen, 2021).

**Types of contract**

There are four different types of electricity contracts in Sweden: fixed price (fast pris), variable price (rörligt pris), mixed (mixavtal) and designated contract (anvisat avtal). Consumers that choose to have a fixed price contracts, pay the same price for electricity regardless of the time of the day in which the electricity is used. These contracts are usually fixed-term, with tie-in periods that can go from a couple of months to 3 years. In variable price contracts, the customer pays a variable price that follows the developments of the Nord Pool price at either hourly or monthly intervals. At the same time, the customer can choose between a rolling variable contract (which can be cancelled with a certain period of notice), or fixed term contract (which cannot be cancelled). Finally there are designated contracts, which are assigned to customers that haven't chosen an electricity contract. Even though designated contracts have 30% higher prices than variable price contracts, they still make up around 11% of the total electricity market.

Electricity consumers in Sweden seem to be abandoning fixed price contracts or designated contracts, and shifting towards variable price electricity supply contracts. By the end of 2019, more than half of Swedish households had a variable price contract, mostly monthly, and 20% a fixed price one (Lusth et al., 2020).

**Taxes**

As previously mentioned, taxes account for almost 43% of the total electricity cost paid by consumers. The most common one is the value-added tax (VAT), which has a value of 25%, and is charged on most goods and services in the EU. Moreover, there is an electricity tax that is not charged as a percentage, but as a fixed amount per every kWh of consumed electricity. The electricity tax is set to 0.331 SEK/kWh (Energimarknadsinspektionen, 2021).

**PV feed-in-bonus**

When it comes to selling PV electricity to the grid, there is a feed-in-bonus program for prosumers that was established on January 1st 2015. It sets a tax credit of 0.60 SEK/kWh for overproduced electricity that is sold to the grid, up to a maximum of 18 000 SEK/yr, equivalent to 30 000 kWh/yr (Lindahl et al., 2021). It is important to mention that the feed-in-bonus is different of a feed-in-tariff, in the sense that the bonus is earned on top of the market price. This program is aimed at micro-producers, which means that they cannot export more electricity than what is purchased over the course of a year. There is currently no specified length of the program, which means that it could be reduced or removed at any time.

## Objective and impact

The aim of this study is to determine what, if any, unsubsidized market conditions could lead to economically motivated self-consumption control strategies with solar heat pumps. This is achieved by performing a sensitivity analysis on the relevant electricity pricing components, taking a case study of a solar PV and ground source heat pump system for a single-family house in Norrköping, Sweden.

This investigation intends to answer the following research questions:

- What is the difference in annual net electricity cost when a solar heat pump system has a smart control strategy to maximize self-consumption?
- What is the effect of reducing and/or removing the feed-in subsidies for overproduced PV electricity on the annual net electricity cost for prosumers?
- What is the effect of varying the volumetric price of the network on the annual net electricity costs for prosumers?
- What happens with the annual net electricity cost when in a capacity grid pricing model, the on-peak and off-peak capacity prices are varied?

A sensitivity analysis is used on multiple pricing models based on current market conditions. Annual electricity cost is used as a comparative KPI between the different pricing scenarios. The results will inform a discussion on whether solar heat pumps should have this type of control or if integration efforts for prosumer PV should be shifted to other market structures and/or technologies, such as peer-to-peer trading, energy communities, and chemical batteries. This study contributes to the literature by holistically evaluating energy supply and storage within a wide range of energy pricing scenarios, which provides additional value beyond typical sensitivity analyses given the rapidly changing products offered to prosumers in deregulated markets.

## Method

For the purpose of answering the research questions formulated in the previous section, a case study representing a typical Swedish single-family house in Norrköping with a ground source heat pump (GSHP), solar PV system, and a smart control strategy to increase self-consumption is utilized. The system is modelled using TRNSYS 18 (Klein et al., 2017), with the simulations being run for an entire year with 3-minute time steps. The meteorological data, obtained from the Swedish Meteorological and Hydrological Institute (SMHI) (SMHI, 2019), and the electricity prices (Nord Pool Spot, 2019), are taken for the year 2019 are used to ensure climate and pricing signatures are aligned.

The single-family house has a built area of 125 $m^2$ and has the characteristics of a Swedish building from the 1960s. Space heating and domestic hot water needs are supplied by a variable speed ground source heat pump, with 5 kW of peak compressor power and 13 kW of heating power. There is a 180 l tank for DHW, but no storage tank for space heating. The ground heat exchanger is a single U-type, non-grouted, 200m deep borehole. A 5 kW roof mounted PV system supplies the electricity needs for the heat pump system. A diagram of the model in TRNSYS is presented in Figure 1.

When it comes to the control strategy, two different operational modes are considered. Firstly, a "normal" operation strategy, in which the heat pump works independently from the PV system. In this case, the heat pump supplies thermal power only based on the occupant´s demand and the top node of the DHW tank is kept at a maximum of 55°C with a dead band of ± 3°C. The other operational mode is a "self-consumption" strategy that aims at increasing the PV self-consumption of the system. This mode activates whenever there is overproduced electricity from the PV system, and consists of increasing the compressor speed of the heat pump to match the available PV power. In this case, the 180-litres DHW tank acts as a thermal storage and the maximum allowed top node temperature is increased to 67.5°C.

The TRNSYS simulations give as a result two different load curves for the electricity demand: the baseline case with a 180 l DHW tank and a normal control strategy (hereon "normal"), and a case with a 180 l tank and control strategy that maximizes self-consumption (hereon "self-consumption"). Technical performance is then evaluated by calculating total annual electricity demand, PV self-consumption (in absolute terms), final annual electricity demand (total annual electricity demand minus the PV self-consumed electricity), electricity demand reduction (as a percentage), self-consumption (as a percentage).

Economic performance is evaluated using annual energy costs and are taken from the perspectives of prosumers, energy retailers, and grid operators, taking as a reference the hourly electricity spot prices from Nordpool for 2019.

A sensitivity analysis on net annual electricity costs is then performed with regards to PV system capacity, grid pricing model, feed-in-bonus and grid variable prices, and compared against the normal operating case with no PV and nominal electricity pricing scheme. In order to set up the nominal electricity pricing scheme, it is necessary to define the main pricing components that are considered for this case, which were presented in the Background section and are summarized in Table 1.

*Table 1. Summary of nominal pricing components*

| | |
|---|---|
| Feed-in-bonus | 0.60 SEK/kWh |
| Fixed annual energy fee | 330 SEK/yr |
| Electricity tax | 0.331 SEK/kWh |
| Supplier fee | 0.050 SEK/kWh |
| VAT | 25% |
| Fixed annual grid fee | 1 530 SEK/yr |
| Volumetric price | 0.317 SEK/kWh |
| On-peak capacity price | 111.50 SEK/kW |
| Off-peak capacity price | 55.57 SEK/kW |

The volumetric price of the network is the only parameter of the above mentioned that had not been defined yet. The value of 0.317 SEK/kWh comes from matching, for the nominal case, the total annual value of the DSO costs for both the energy and capacity pricing models. The procedure of matching the cost for both network pricing models, helps establish a relationship between fixed and variable costs without changing the total network cost to the customer, and serves as a common starting point for both pricing models. This can be seen in Table 2 for the energy pricing parameters and the capacity pricing parameters.

Following on the economic analysis, there are two types of pricing sensitivities that are performed within the scope of this study: one with constant annual DSO costs where both fixed and variable prices change, and another where fixed prices are kept constant at the nominal value of 1530 SEK/yr and only variable values change. For each of the two pricing sensitivities, the following parameters are varied: PV system capacity, type of grid pricing contract, feed-in-bonus, volumetric tariff, off-peak capacity price and on-peak capacity price. It is worth noting that for the sake of lowering the amount of pricing scenarios, the off-peak and on-peak capacity prices are varied simultaneously.

*Table 2. Energy and capacity pricing component variation for constant DSO cost*

| | Volumetric SEK/kWh | Off-peak SEK/kW | On-peak SEK/kW | Grid variable SEK/yr | Grid fixed SEK/yr | Total DSO cost SEK/yr |
|---|---|---|---|---|---|---|
| 70% | 0.222 | 78.05 | 39.025 | 1 917 | 2 352 | 4 269 |
| 80% | 0.254 | 89.20 | 44.600 | 2 191 | 2 078 | 4 269 |
| 90% | 0.285 | 100.35 | 50.175 | 2 465 | 1 804 | 4 269 |
| 100% | 0.317 | 111.50 | 55.750 | 2 739 | 1 530 | 4 269 |
| 110% | 0.349 | 122.65 | 61.325 | 3 013 | 1 256 | 4 269 |
| 120% | 0.380 | 133.80 | 66.900 | 3 287 | 982 | 4 269 |
| 130% | 0.412 | 144.95 | 72.475 | 3 561 | 708 | 4 269 |

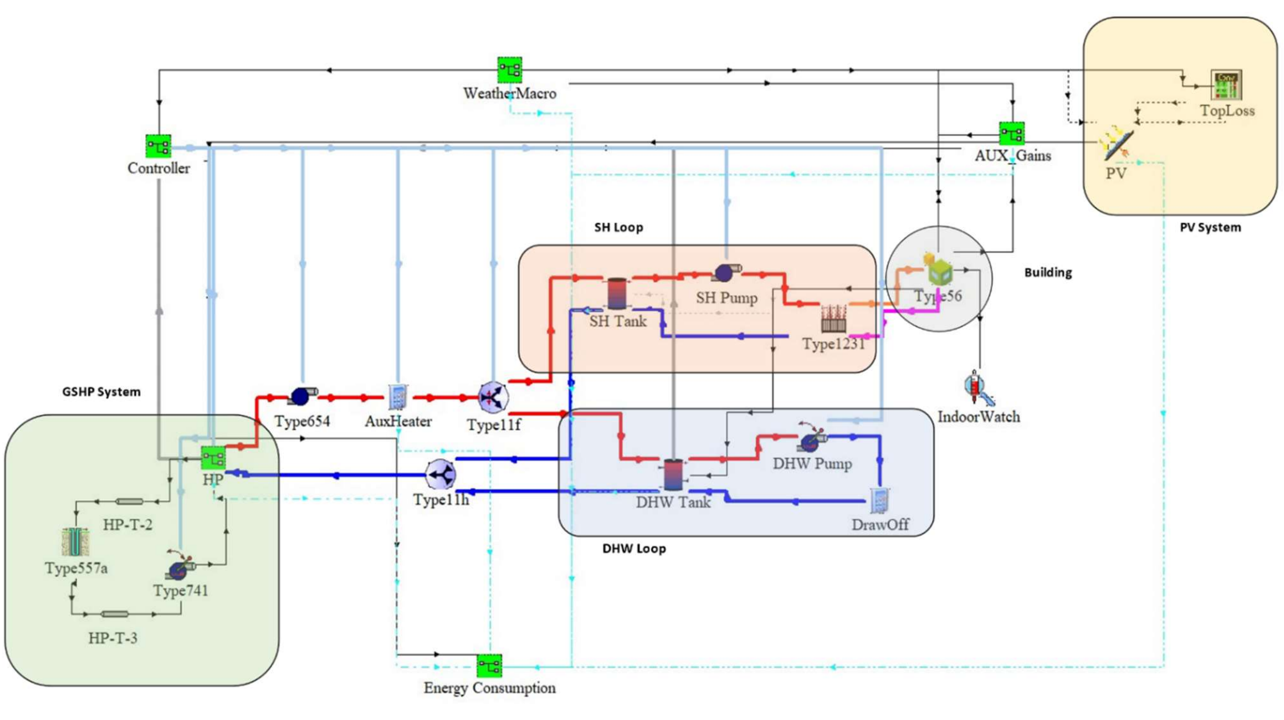


*Figure 1. TRNSYS model of PV + GSHP system for single-family house in Norrköping*

A summary of the parameters that are varied for the sensitivity analysis is presented in Table 3.

*Table 3. Sensitivity parameters*

| | |
|---|---|
| PV capacity | 3 kW, 5 kW, 7 kW |
| Grid pricing model | Energy, Capacity |
| Feed-in-bonus [SEK/kWh] | 0, 0.20, 0.40, 0.60 |
| Volumetric price | 0%, ±10%, ±20%, ±30% |
| Off-peak price | 0%, ±10%, ±20%, ±30% |
| On-peak price | 0%, ±10%, ±20%, ±30% |

## Results and discussion

The results from the sensitivity analysis on the 3 kW and 7 kW PV system capacity give a similar trend to the 5 kW case, so for the sake of simplicity, only the results for the 5 kW PV system are presented in these sections. Tables and figures obtained for the other two PV system capacities are not shown in this section. The first thing that can be noticed when looking at the energy data summary presented in

Table 4, is the difference in annual demand between the normal and self-consumption (SC) cases. This is due to the fact that with the SC strategy, more electricity is supplied to the heat pump when we increase the maximum top node temperature of the tank to 67.5°C. However, the final annual electricity consumption is reduced by an extra 3% when the SC strategy is active. The results from the simulations also show an increase of 308 kWh in the amount of PV electricity self-consumed by the building for the SC case, which is 7% more in absolute terms than for the Normal case. This means that half of the electricity generated by the PV system is self-consumed, while the other half is sold back to the grid.

*Table 4. Energy data summary*

| | **Normal** | **SC** |
|---|---|---|
| Annual demand [kWh/yr] | 8 646 | 8 646 |
| Annual PV generation [kWh/yr] | 4 851 | |
| PV self-consumption [kWh/yr] | 2 147 | 2 455 |
| Final annual demand [kWh/yr] | 6 498 | 6 341 |
| PV overproduction [kWh/yr] | 2 703 | 2 395 |
| Demand reduction | 25% | 28% |
| PV self-consumption | 44% | 51% |

Table 5 shows the effect of grid pricing model, feed-in-bonus and variation in volumetric, on-peak and off-peak pricing on the net annual electricity cost for the customer, when DSO costs are kept constant. It can be seen that the capacity pricing model gives an annual net electricity cost 10% higher on average than the energy pricing model. As we increase the feed-in-bonus, the net cost decreases due to the increasing revenues from selling electricity to the grid. Finally, as the variable price decreases, the net cost increases. This is mainly due to the fact that the fixed part increases in order to keep a constant DSO price, and it becomes more relevant in the pricing structure. When comparing the baseline with normal operation against the optimized self-consumption case, it can be seen that for the energy pricing model, it becomes slightly better to have a self-consumption algorithm than a normal operation strategy when the volumetric price increases over the nominal value. For example by increasing the variable price a 10%, net cost is reduced by almost 2%. However for the capacity grid pricing model, it can be seen that by only looking at net annual cost, a self-consumption control strategy does not add any value in the studied pricing range.

*Table 5. Sensitivity on net cost when total DSO cost is constant*

| | Energy Contract | | | | Capacity Contract | | | |
|---|---|---|---|---|---|---|---|---|
| Feed-in-bonus [SEK/kWh] | 0 | 0.20 | 0.40 | 0.60 | 0 | 0.20 | 0.40 | 0.60 |
| Normal | 10,435 | 9,894 | 9,354 | 8,813 | 11,120 | 10,579 | 10,039 | 9,498 |
| -30% | 10,625 | 10,145 | 9,666 | 9,187 | 11,197 | 10,718 | 10,239 | 9,760 |
| -20% | 10,536 | 10,057 | 9,578 | 9,098 | 11,188 | 10,709 | 10,230 | 9,751 |
| -10% | 10,439 | 9,960 | 9,481 | 9,002 | 11,179 | 10,699 | 10,220 | 9,741 |
| 0% | 10,350 | 9,871 | 9,392 | 8,913 | 11,169 | 10,690 | 10,211 | 9,732 |
| 10% | 10,261 | 9,782 | 9,303 | 8,824 | 11,160 | 10,681 | 10,202 | 9,723 |
| 20% | 10,164 | 9,685 | 9,206 | 8,727 | 11,151 | 10,671 | 10,192 | 9,713 |
| 30% | 10,075 | 9,596 | 9,117 | 8,638 | 11,141 | 10,662 | 10,183 | 9,704 |

*Table 6. Sensitivity when grid fixed fee is constant*

| | Energy Contract | | | | Capacity Contract | | | |
|---|---|---|---|---|---|---|---|---|
| Feed-in-bonus [SEK/kWh] | 0 | 0.20 | 0.40 | 0.60 | 0 | 0.20 | 0.40 | 0.60 |
| Normal | 10,435 | 9,894 | 9,354 | 8,813 | 11,120 | 10,579 | 10,039 | 9,498 |
| -30% | 9,597 | 9,118 | 8,639 | 8,160 | 10,170 | 9,691 | 9,212 | 8,732 |
| -20% | 9,851 | 9,372 | 8,893 | 8,413 | 10,503 | 10,024 | 9,545 | 9,066 |
| -10% | 10,096 | 9,617 | 9,138 | 8,659 | 10,836 | 10,357 | 9,878 | 9,399 |
| 0% | 10,350 | 9,871 | 9,392 | 8,913 | 11,169 | 10,690 | 10,211 | 9,732 |
| 10% | 10,604 | 10,125 | 9,646 | 9,166 | 11,502 | 11,023 | 10,544 | 10,065 |
| 20% | 10,849 | 10,370 | 9,891 | 9,412 | 11,836 | 11,356 | 10,877 | 10,398 |
| 30% | 11,103 | 10,624 | 10,145 | 9,666 | 12,169 | 11,690 | 11,211 | 10,732 |

Table 6 shows the effect of grid pricing model, feed-in-bonus and variation in volumetric, on-peak and off-peak pricing on the net annual electricity cost for the customer, when variable prices are changed and the fixed fee is kept constant at 1530 SEK/yr. The capacity pricing model gives an annual net electricity cost 10% higher in average than the energy pricing model, same as for the case with constant DSO costs. It can also be seen that as we increase the feed-in-bonus, the net cost decreases due to the increasing revenues from selling electricity to the grid. Finally, as the variable price decreases, the net cost also decreases. This is expected since by keeping the fixed fee constant, at lower variable prices we get lower net electricity costs. It is worth noting that for both the energy and capacity grid pricing models, the benefits of having a self-consumption strategy become better as the volumetric price falls below the nominal value. For example, by decreasing the variable price a 10% from the nominal value, the net cost can be reduced by almost 3% for both cases.

The following graphs show a breakdown of the annual net electricity cost into the different pricing components: electricity, network, taxes, fixed fees and revenues. The results of varying the feed-in-bonus, volumetric price, on-peak price and off-peak price for the case with a self-consumption strategy are plotted against the normal operation case. Figure 2 shows the results of the sensitivity analysis for an energy grid pricing contract and a constant DSO total cost. It can be seen that there is a very small variation in net cost when the variable price and feed-in-bonus are varied. When increasing the variable price by 10% for the case with no-feed-in-bonus, the annual net cost decreases by 0.85%. However, when we consider a feed-in bonus of 0.60 SEK/kW, increasing the variable price by 10%, decreases the net cost by 0.99%. Although the difference is rather low, it can be seen that a change in variable prices has a greater impact on net cost at lower or no feed-in-subsidies than it does at the nominal one. On the other hand, increasing the value of feed-in-bonus by 0.20 SEK/kWh, increases PV revenues by 33% and reduces the annual net electricity costs by approximately 5%.

Figure 3 shows the results for a capacity grid pricing contract, when variable and fixed prices are adjusted so that the network cost is kept constant. The first thing that can be inferred from the graph, is that the annual costs are less sensitive to changes in capacity price when DSO total costs are kept constant. Normal operation seems to be more beneficial for the customer for the different feed-in-subsidies cases, with the difference growing as feed-in-subsidies grow. However, going from normal operation to a self-consumption strategy or varying the off and on-peak capacity prices has little or no effect on net costs. It is worth noting however, that as we increase the feed-in-bonus, the PV revenues also increase, reducing the net cost by around 5% for every 0.20 SEK/kWh increase.

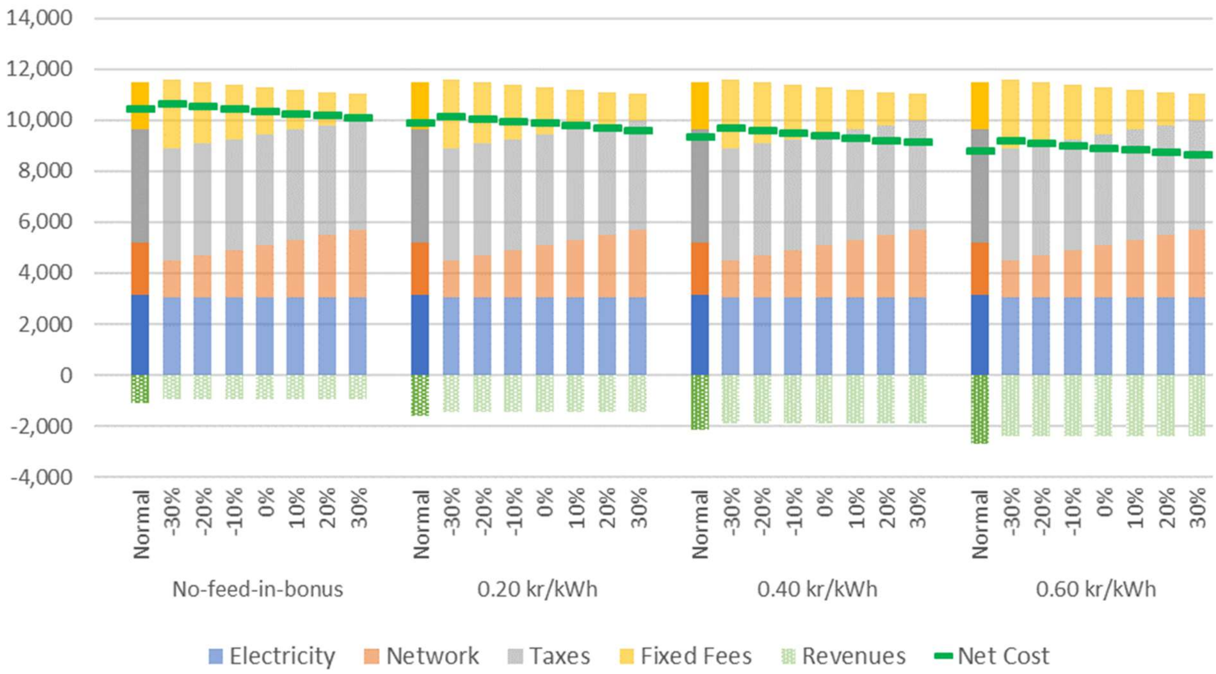


*Figure 2. Sensitivity for energy grid pricing model when total DSO costs are kept constant*

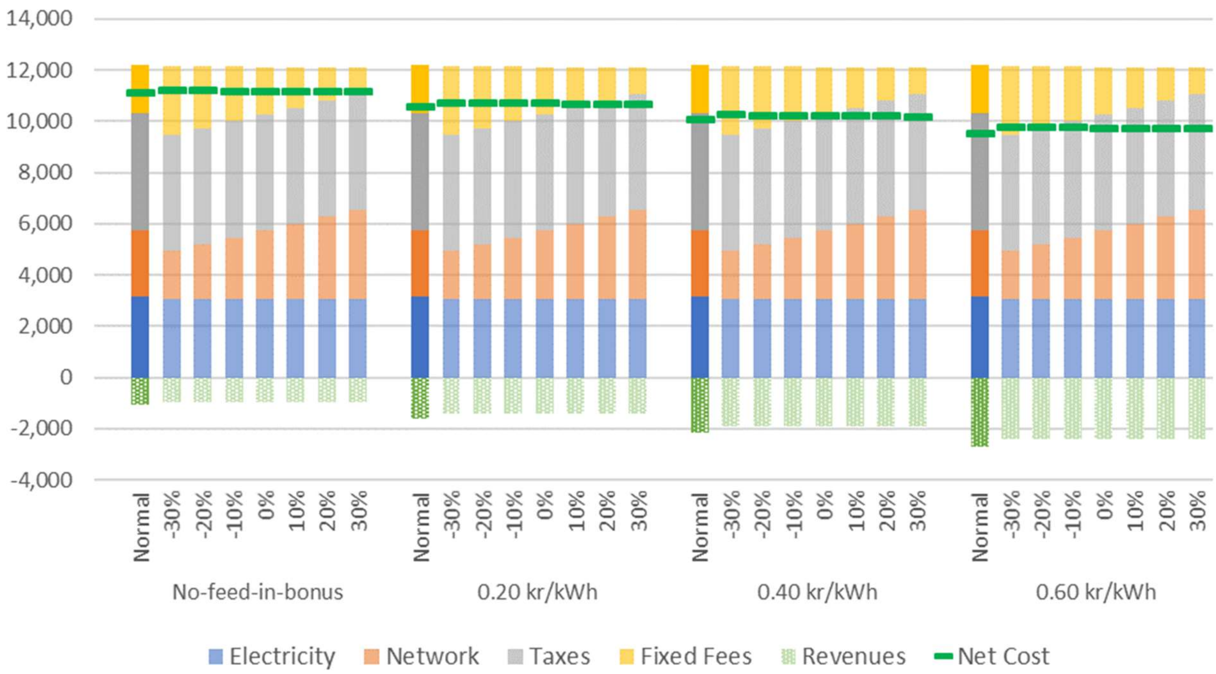


*Figure 3. Sensitivity for capacity grid pricing model when total DSO costs are kept constant*

Figure 4 and Figure 5 show the economic results for an energy and capacity grid pricing contract (respectively), when the volumetric price, on-peak capacity price and off-peak capacity price are varied, while keeping the fixed price constant. Since the total network price was not kept constant, a greater change in net cost can be appreciated as the different parameters are varied. As it was expected, it can be seen once more that by increasing the feed-in-bonus, the net cost decreases due to an increase in PV revenues from selling overproduced electricity to the grid. It can also be observed that by increasing the variable price a 10%, the annual net cost is increased by 2.5% for the energy grid pricing model, and by 3% for the capacity grid pricing model. On the other hand, increasing the value of feed-in-bonus by 0.20 SEK/kWh, increases PV revenues by 33% and reduces the annual net electricity costs by approximately 5%.

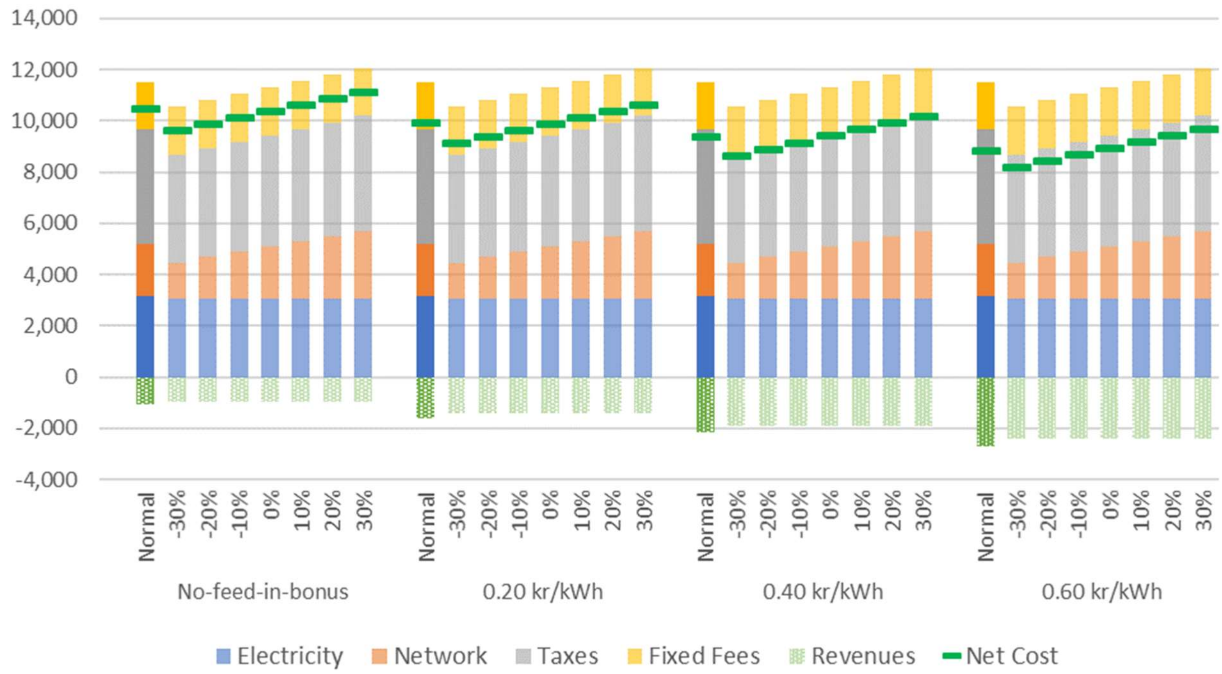


*Figure 4. Sensitivity for energy grid pricing model when grid fixed fee is kept constant*

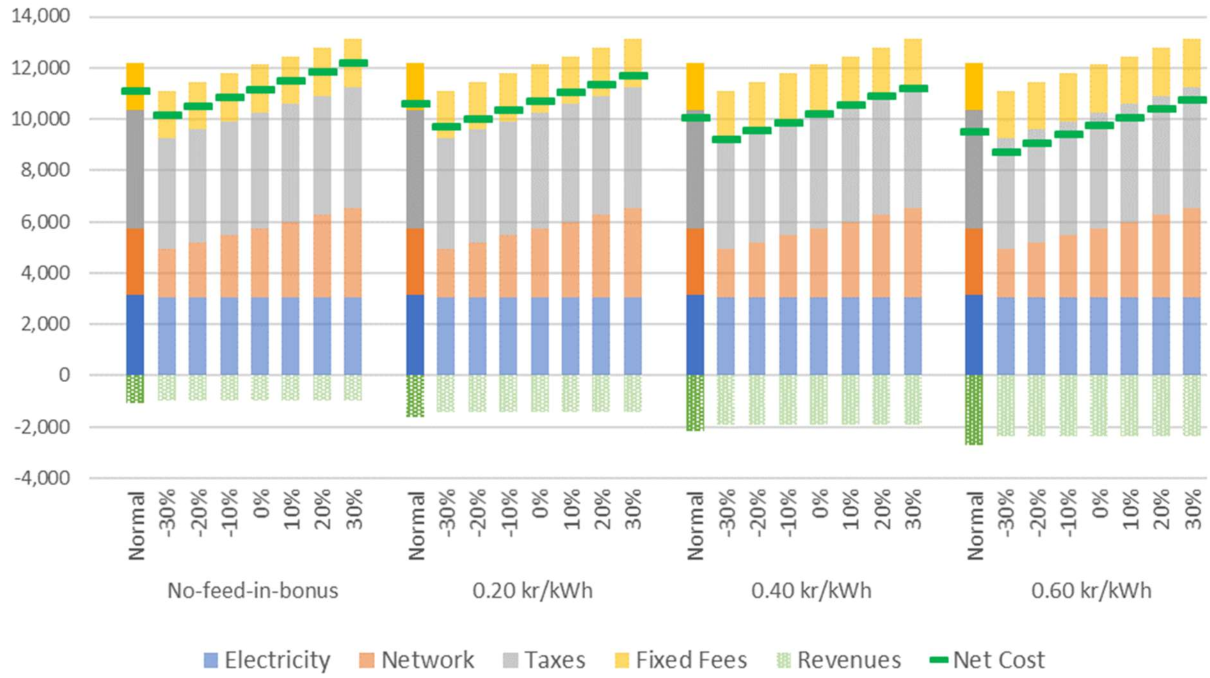


*Figure 5. Sensitivity for capacity grid pricing model when grid fixed fee is kept constant*

## Conclusions and future work

An important outcome of the study is that self-consumption algorithms have very little impact on net costs for the customer, regardless of grid pricing model or price variation. When nominal pricing conditions and no feed-in-subsidies are considered, changing from a normal control strategy to a control strategy aimed at maximizing self-consumption, increases self-consumption from 44% to 51%, but the changes in total net electricity cost are less than 1%. Net costs are reduced by 0.81% for an energy grid pricing contract, and increased by 0.44% for a capacity pricing contract. In absolute terms, the difference is of -85 SEK/yr and +49 SEK/yr respectively. Most probably, this is due to the overproduction of PV electricity occurring at times of the day when there is no heating demand, When feed-in-subsidies of 0.60 SEK/kWh are considered, net costs are increased by 1.13% and 2.46% for energy and capacity grid pricing contracts respectively, which in absolute terms means an increase of +100 SEK/yr and +234 SEK/yr.

Feed-in-bonus is the most important aspect when comparing different pricing schemes, and no other sensitivity comes close. When varying the volumetric tariff and peak capacity pricing while keeping the fixed fee constant, there is a considerable variation in net cost that could be compared with the effect of feed-in-subsidies. However, this is not realistic under current business models since it would mean that the electricity retailers would have to lower their earnings. By increasing the feed-in-subsidies by 0.20 SEK/kWh, revenues from selling overproduced electricity increase by 33% and net costs are reduced by 5% clearly demonstrating its impact.

Two types of pricing sensitivities were performed within the scope of this study; one with constant annual DSO costs where both fixed and variable prices were changed, and another where fixed prices were kept constant at the nominal value of 1530 SEK/yr and only variable values changed. For the case with constant annual DSO costs, the effect of varying the volumetric price of the network is almost negligible for the capacity grid pricing model, but slightly higher for the energy pricing model. For every 10% increase in the variable price, the net cost decreases by 0.09% and 0.9% in average respectively.

For this particular case study, the energy grid pricing model ends up being more beneficial for the prosumer (less cost), but when looking at it from the electricity retailers perspective, a capacity grid pricing model would generate more earnings. However, the capacity grid pricing model is less sensitive to the effect of the different pricing components, so it would be more advantageous for PV owners, assuming the prices are set for non-PV owners to be equal to that of a volumetric tariff.

Limited storage capacity of a domestic how water tank is the main limitation when it comes to achieving high self-consumption, and it was shown in this study that different pricing strategies and incentives have little effect on improving this situation. The presence of battery storage to store the excess electricity from the PV to be used at times during the day when there is no solar irradiation could be a possibility to revert this situation. A future study could compare the life cycle costs of using heat pump controls, which can be done at no cost but generates low gains, against a battery storage solution, which costs more but provides higher gains.

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