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Future network loading and tariffs with electric vehicles

Exploiting data from 1 million customers

Axel Philipson
Hampus Lavin

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

Abstract

Electric vehicles have received a lot of attention lately and are expected to boom in the near future. In the power grid industry this raises concern on whether the grid is dimensioned to handle the power peaks related to charging. Solar cells are also a hot topic when discussing future energy supply and how it will impact on the grid.

Initially this thesis gives insight to the current state of solar cells and electric vehicles, which charging techniques that are being used and future prospects of both technologies. Thereafter, investigation goes into how the grid is utilised today using mathematical statistics and what the load situation will look like with a large scale introduction of electric vehicles. A case study in a stressed grid with a high penetration of electric vehicles is also done to showcase impact of solar cells. Specifically loading of secondary substation transformers, cable loadings and voltage drops are analysed to find limitations.

Key results are that the grid in general has sufficient capacity with good margin to the highest expected peak in power and that the current tariff structure would generate a large income stream if home charging would become more common. The results from the case study in a stressed grid shows that even if transformer loading is high , the cable capacities are sufficient to avoid overload. Also, the slightly larger voltage deviations are still well within E.ON guidelines. Solar cells delivers most energy mid-day when charging does not occur, and therefore do not reduce power peaks.

In conclusion, E.ON should not be concerned about a large scale introduction of electric vehicles, rather welcome it. The tariff should not be capacity based on account of electric vehicles since there is little risk that their charging will overload the grid. Moreover, the current tariff structure benefits greatly from an increase in consumption and higher peaks, which leads to more billable kilowatt-hours and upgrades of fuses. There are of course other arguments for a capacity based tariff, but these are not treated here. The calculated resulting annual revenues are 213 MSEK and 430 MSEK for 20% and 40% electric vehicles respectively.

Keywords: Electric vehicles, Charging, Utilisation, Power peaks, Photovoltaics

Sammanfattning

Elbilar har fått mycket uppmärksamhet den senaste tiden och förväntas öka explosionsartat i antal den närmaste framtiden. Inom elnätsbranschen finns det en oro kring hurvida elnätet kommer klara av de effekttoppar som laddning orsakar. Solceller är också ett hett ämne i diskussionen kring framtidens energiförsörjning och belastning av elnätet.

Till en början ger detta arbete insikt i hur läget för solceller och elbilar ser ut nu. Vidare belyses olika laddningstekniker som används till elbilar och framtidsutsikter för de båda teknikerna. Därefter undersökes hur elnätet är utnyttjat idag med matematisk statistik och hur dess last kommer att påverkas av en storskalig introduktion av elbilar. En fallstudie i ett högt belastat nät med hög andel elbilar gjordes för att visa på inverkan av solceller. Laster i alla kablar och spänning hos kunder analyserades även för att se om detta kan vara ett problem.

Viktiga resultat är att elnätet är väldimensionerat med god marginal mot effekttoppar samt att den nuvarande tariffmodellen skulle generera en stor inkomst om hemmaladdning skulle börja uppstå. Resultatet från fallstudien i ett högt belastat nät visar på att även om transformatorns belastning är hög, så föreligger det låg risk för kablarna att överbelastas. Något högre spänningsfall uppstår i nätet, men de ligger dock väl inom ramen för E.ONs riktlinjer. Solceller levererar mest energi under dagen när laddning inte sker, och reducerar därför inte effekttoppar.

Sammanfattningsvis borde E.ON inte vara oroliga för en storskalig introduktion av elbilar utan snarare välkomna en sådan. Tariffen bör inte vara effektbaserad med anledning av elbilsladdning då det är låg risk för överbelastning i elnätet. Vidare gagnar nuvarande tariff stort från en ökning i fakturerbara kilowattimmar samt säkringsuppgraderingar. Det finns naturligtvis andra argument som talar för en effektbaserad tariff, som dock inte utreds här. De framräknade slutliga årliga intäktsökningarna blev 213 MSEK och 430 MSEK för 20% respektive 40% elbilar.

Nyckelord: Elbilar, Laddning, Utnyttjandegrad, Effekttoppar, Solceller

Preface

We would like to state our gratitude towards E.ON Elnät for giving us the opportunity to do a master thesis for them. Special thanks go out to Rickard Venetjoki who has been putting in a lot of time to ensure high quality results. We would also like to thank other employees at E.ON who have been very helpful and made this possible. Peter Andersson, Torbjörn Stenström, Thomas Pehrsson and Ingemar Leisse have given tremendous support and help in various of situations along the way. From the side of LTH we have received great guiding from our supervisor Olof Samuelsson who continuously has reviewed and questioned our work which have elevated it to a higher academical level. Our gratitude also goes to Erik Lindström who helped us at an early stage with the mathematical statistics.

Terminology

EV	Electric Vehicle
BEV	Battery Electric Vehicle
PHEV	Plug-In Hybrid Electric Vehicle
PV	Photovoltaics (solar cells)
SALAR	Swedish Association of Local Authorities and Regions
SCB	Statistiska Central Byrån
ICE	Internal Combustion Engine
SoC	State of Charge
SD	Standard Deviation
OBC	On Board Charger

Contents

1 Introduction

The transport sector stands at the dawn of a big transformation where traditional fossil fuels are being exchanged with renewable equivalents. EVs (Electric Vehicles) grow in popularity each year and are believed to make up the majority of the transport sector at the end of the transformation. Multiple leading nations have set strict emission goals, where recently Germany put a proposition forward to completely ban fossil driven vehicles 2030 (Forbes, 2016). Sweden has made priorities to make the country's vehicle fleet fossil independent by 2030 (Regeringen, 2009b) and Malmö city has officially set the goal to be completely fossil free 2030 (Regeringen, 2009a).

The world's production of electricity has seen a large increase of renewable sources, mainly wind power but also PVs (Photovoltaics). In the Nordic area wind power has been the dominant of the two by far. Though PVs are slowly starting to increase in market shares and forecasts have estimated that it could constitute 5-10% of Sweden's production of electricity by 2040 (Energimyndigheten, 2016b). This raises the question how PV systems will cope with the development of EVs. Particularly in northern countries were sun power is not present during the grid's critical hours.

The development of BEVs (Battery Electric Vehicles) and mainly their batteries has greatly accelerated the last few years. Up to this date, the power grid has not been stressed by the energy consumption of the transport sector. With a large scale introduction of BEVs, the grid is expected to provide the transport sector with the energy it needs beyond the regular consumption. In the energy sector, the amount of energy needed is not considered an issue, it's the concern of how to handle the inevitable larger capacity peaks. The peaks are assumed to arise during evenings when the population gets home from work and consequently wants to charge their vehicles, though not so much during the rest of the day. To rebuild large parts of the grid due to such a short capacity peak is not socioeconomically profitable, which is the reason why a network tariff based on capacity is assumed to be the price model of the future. However, amongst some there's a concern that this has become a truth on unfounded arguments. As a matter of fact, in Sweden today many substations are loaded by 60% of the rated power. This is due to the low cost of equipment relative to the high cost of labour and excavation, which leads to the largest transformer being installed.

1.1 Purpose

The study aims to conclude the situation of the grid with respect to handling the introduction of EVs at the end customers. Moreover, today's tariff structure will be evaluated with this new consumption pattern. The purpose will be fulfilled by answering the question formulations below.

1.2 Problem statements

- How well-dimensioned is the distribution grid today?
- Will the grid be stressed in a way that can lead to local capacity shortage if many BEVs are charged simultaneously?
- Will investments have to be made in the grid?
- Could possible power peaks be reduced by PV systems?
- What consequences does this have to E.ON with today's energy based tariff?

1.3 Company description E.ON

This thesis is done in collaboration with E.ON and uses data from the 1 million customers connected to their distribution grid in Sweden. Although the analysis is made on E.ON's grid, the results should be applicable for other grid owners.

E.ON is a global conglomerate with headquarters in Germany. By the year of 2001 E.ON bought the majority of the Swedish electricity company Sydkraft and is now the largest owner of power grids in the south of Sweden. Since 2016 E.ON has been divided into two companies, E.ON Sweden and Uniper. Uniper took ownership of all conventional electricity production while E.ON took control of distribution (electricity, heat and gas), renewable energy and customer relations. An overview of E.ON Sweden is given in figure 1.

Today E.ON Elnät (which is a part of E.ON Sweden) has the responsibility for maintenance and development of its sub-transmission and distribution grid. E.ON Elhandel has the responsibility of selling the electricity while E.ON Elnät charge their customers based on their impact on the power grid. For all grid owners there are certain laws and regulations about communication between electricity traders and power grid owners (unbundling). This results in that both companies are run independently of each other.

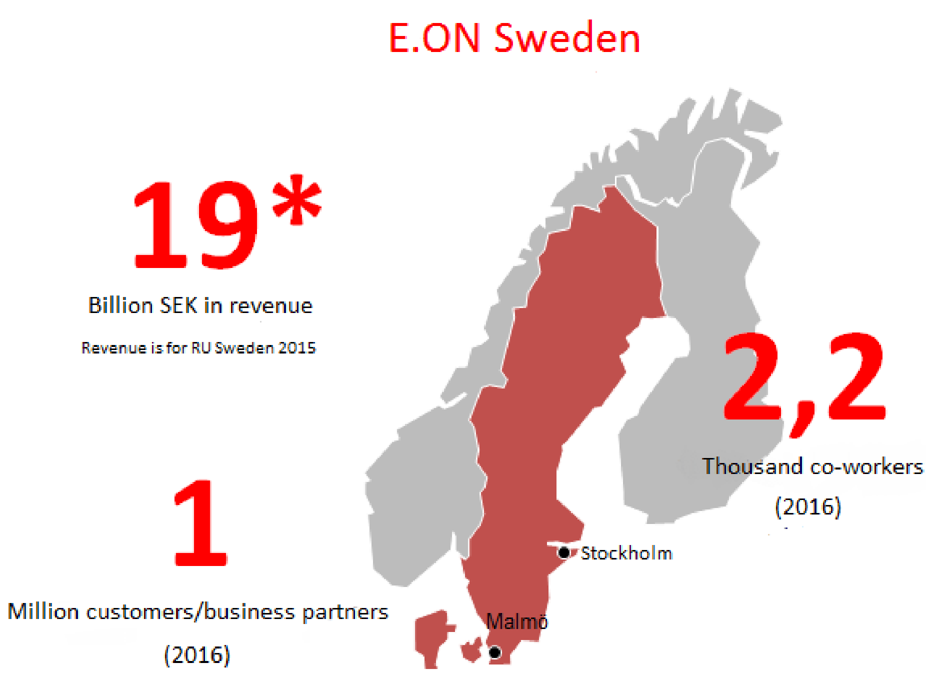


Figure 1: Overview E.ON Sweden's operations

1.4 Limitations

This thesis will attempt to give grounds for decision makers only regarding future tariff structures. We will only evaluate how E.ON will benefit with the current tariff, not suggest a new tariff model. In many cases we will not do a detailed model of a scenario, rather take a simplified model that resembles the worst case. Finally, we will only consider low voltage distribution grid including the secondary substation transformers in our analysis and that the grid are identical to today in 2030.

1.5 Outline

Chapter 2 - Short chapter describing the general methodology of the study.

Chapter 3 - This chapter will give an introduction to EVs and PVs. Basic concepts will be gone through as well as market penetration and future outlook. Different charging techniques are explained such as normal, semi-fast and fast charging. Charging patterns will also be touched upon.

Chapter 4 - The structure of the electricity network in Sweden is explained and visualised. The substation types and their field of usage are clarified. Then tariffs are thoroughly gone through in the following sub chapters. Different tariff types are mentioned as well as how they are designed and what is factoring in when setting the tariffs.

Chapter 5 - Describes the whole process of estimating the load situation in the distribution grid when introducing EVs. After the loads have been determined, consequent costs and revenue streams are estimated.

Chapter 6 - Presents the methodology and results of a case study in a stressed grid in Järfälla. Different scenarios of EVs and PVs are considered. Multiple key measurements are brought forward such as cable loadings and voltage drops.

Chapter 7 - The results and methodology from chapter 2, 5 and 6 are thoroughly discussed. Shortcomings and liabilities as well as possibilities are suggested. The authors bring forward their thoughts and opinions on the work that has been done.

Chapter 8 - Concluding thoughts and recommendations on the thesis. Additionally, future work is suggested here.

2 Method

This chapter provides a summary of the methods used to achieve the answers to the earlier formulated problem statements.

2.1 General method description

The first problem statement is simple yet hard to answer, though a very important stepping stone to enable answers to the other problems formulated. Knowledge of power systems and how they are designed is needed here. This is brought in *Chapter 4 - The distribution grid and tariffs*. Also, insight in mathematical statistics and processing of big data is required, which is explained in *Chapter 5.1 - Regression Models*. With yearly consumption from one million customers estimated load curves was created for all substations. By using the power system analysis software DPG.Sim, cable loading and voltage deviation could also be studied, this is done in *Chapter 6 - Case study in a stressed grid*.

The second problem statement is slightly more complex. Its nature is very wide and requires literature studies that spans across multiple fields. A fundamental knowledge of technology trends, politics (subsidies - current and probable future ones), consumer behaviour as well as grid structure is required to answer the question. These key points are described in depth in *Chapter 3 - EV and PV overview*. The future of EV scenarios are divided into three cases: today, base case and high case. With consumptions created, estimated EV charging was applied to single family homes - where charging can occur without notice. The impact from EVs on the grid was further investigated in the case study.

The third problem is highly related to the previous ones, and requires the same background knowledge in pair with investment costs of substations. This is found under *Chapter 4 - The distribution grid and tariffs*. With upgrade costs and data on overrun hours the investment need could be estimated.

The fourth question requires basic knowledge about PV systems to be evaluated. An introduction is given to this in *Chapter 3 - EV and PV overview*. In *Chapter 6 - Case study in a stressed grid* the impact from PV systems combined with charging of EVs was analysed.

Finally, to give an adequate answer to the last question, the combined results of the earlier questions will be used. Together with basic understanding of fees and tariffs used in the distribution and sub-transmission grids, different scenarios are set up.

3 EV and PV overview

This chapter gives an introduction to the core concepts of this thesis. Firstly insight is given in the current state and the future of EVs. Thereafter the same is done for PV systems.

3.1 Electric vehicles

The growth curve of EVs is very steep today with an average increase of roughly 100% the past two years. PHEV (Plug-in Hybrid Electric Vehicle) is still the dominating type in Sweden, with 2/3 of the market. Worldwide it is almost even between the two (CO, 2016). However, the general belief is that PHEV merely is a transition car to BEV, not the final solution.

Figure 2: Popular electric vehicles, from left: Tesla Model S (BEV), Nissan Leaf (BEV) and Volvo C30 (PHEV).

The reach of BEVs is often argued to be too short and limiting. While this was true some years ago, and for some models still is, newer cars like the Tesla S (see figure 2) has a range of up to 500km. This makes the BEV an interesting case for people outside of the city centres, maybe as far out as the countryside. It also makes it more than a vehicle for just commuting - with this range it's a legitimate alternative when travelling longer distances. Though statistically, very rarely does the average person drive distances this far. As a matter of fact, the average distance in Sweden per day and per person is 28km, which makes the short range Nissan Leaf (175km reach at best) a very viable option.

3.1.1 BEV

BEV notates the fully electric variant of electric vehicles and has least local environmental impact, with its non-existing emissions. It is debated though, if during its whole life cycle, it is more environmental friendly than its fossil driven equivalent. This depends on how the electricity that charged the battery was produced (e.g. wind power better than coal). There's also a lot of environmental impact connected to the production of batteries. However, as battery technology and development of BEVs overall progresses, it's expected that the gap between them will grow to make the BEV the given choice from an environmental perspective.

3.1.2 PHEV

This is the hybrid model of the electric vehicle and normally carries a significantly smaller battery than its fully electric equivalent. It is often sufficient for average daily traffic though, with its range of about 50km. On days where the temperature deviates a lot from 20°C, the range would be shorter and the ICE (Internal Combustion Engine) might have to be used. The energy consumption per 10km is somewhat higher of a PHEV than of the BEV.

3.1.3 Charging techniques

BEVs are dependent on being continuously charged. The various charging methods stress the grid differently and therefore play a key role when dimensioning future grid infrastructure. The only commercially available method of charging today is plug-in charging, i.e. the vehicle is connected to the grid via a cable. Other prospects are charging via induction or swapping the battery, however these are not seen in a large scale today.

The charging of a battery should be DC. Therefore to enable AC charging, all EVs have an On Board Charger (OBC) which directs the current and the voltage. Charging of EVs is done with different charging powers, resulting in different charging times. If the charging power is high, the rectifier can be placed in the station instead due to lack of space and a high price. High power charging results in shorter charging time and vice versa. There are no official classifications made, but charging techniques are usually divided into three types: normal, semi-fast and fast charging. For the various types, different charging contacts are used and are presented first.

Charging contacts and standards

Which contacts that should be used has been a debated subject. Both which contact should be used between cable and station as well as contact between cable and car. If charging at a public station, the latter need only to be considered. The often seen contacts in figure 3 are

Figure 3: Standrad contacts, from left: Schuko, Industrial contact one phase, Industrial contact three phase (Elsäkerhetsverket, 2014)

not suited for charging of EVs. The Schuko should not be used for continuous load due to fire hazard. Moreover, none of them has extra pins for communication between station and car. The prevailing new contacts are shown in figure 4. As can be seen in the picture, they have 2 extra pins for communication between station and car. The communication is used to ensure the charging is safe and doesn't cause unnecessary stress to the battery. For instance, the last 20% are charged with a lower power.

Type 1 is designed for one phase current up to 32A. Type 2 is meant to handle single phase up to 70A or three phase up to 63A. This contact has been defined as the standard for charging EVs in Europe. The last one is called Combo 2 and can handle both AC and DC, it is global standard also known as CCS. The upper part is Type 2 and is used for normal and semi-fast

Figure 4: New generation contacts, from left: Type 1, Type 2, Combo 2 (Elsäkerhetsverket, 2014)

charging, while the lower part is used for high power DC fast charging (Elsäkerhetsverket, 2014).

Normal charging

This is the most common type where the charging is done with low power (3.7 kW) during long time. Usually this results in loading times somewhere between 6-10 hours with empty battery. The time varies depending on the available power and the size of the battery. Most often it is one phase with 230V/16A. This method is good for topping up the battery, but is also suitable for charging night time if the battery has a low state of charge (Elsäkerhetsverket, 2014).

Semi-fast charging

This type of charging is usually done with 7.4kW, 11kW and even up 22kW (400V/32A). Its main application so far is parking spots where the car is expected to be stationary for at least half an hour. It can be one phase but also three phase or DC. With 22kW, the average battery is 80% charged after about 45 minutes. With 7.4kW the time would be somewhere between 2-3 hours (Elsäkerhetsverket, 2014).

Fast charging

Fast charging is considered to be everything from 50 kW up to Tesla's super charger at 125kW. As the title implies the goal is to achieve fast charging. There is no official max wait time, but it should be fast enough for the driver to wait while charging. Its main application is along highways where longer distances are naturally travelled. It can also be applicable in cities for frequent drivers like taxis and delivery vehicles or private persons who lacks the opportunity to charge at home (Elsäkerhetsverket, 2014).

3.1.4 Market penetration

There are roughly 28 000 EVs totally in Sweden today, where 30% are BEVs. From figure 5 it can be seen that Mitsubishi has acquired a big (roughly 25%) market share with its PHEV model Outlander. Within the BEV category the Tesla is in the lead with its Model S85. 2017

EVs constitute only shy of 0.5% of the vehicles in Sweden. Though, during 2015 2.4% of total cars sold were EVs. Figure 6 displays the exponential growth of EVs recent years and figure 7 shows the current distribution between PHEVs and BEVs.

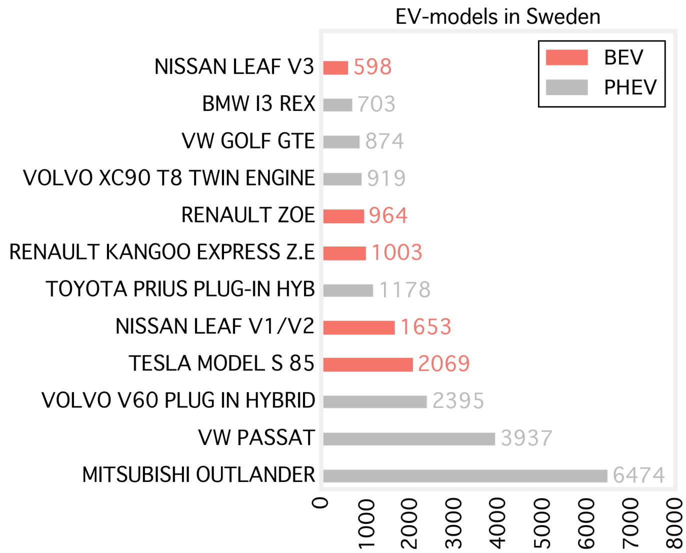


Figure 5: Most sold EVs in Sweden. Source: PowerCircle (2016)

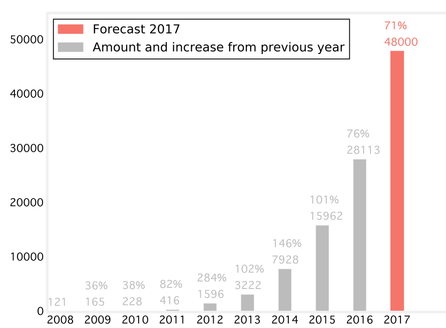


Figure 6: Accumulated increase of EVs per year. Source: PowerCircle (2016)

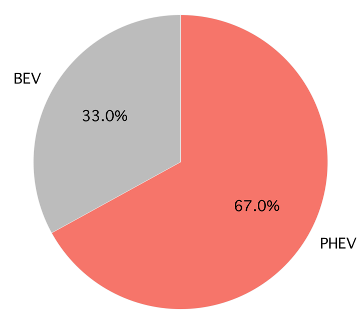


Figure 7: Distribution between PHEVs and BEVs. Source: PowerCircle (2016)

Energy consumption

From the current EVs available today energy consumption per km is widely spread. In general PHEV have a higher energy consumption per km than BEV. In table 1 the 5 most popular PHEVs and BEV together with their consumption per 10km are displayed (PowerCircle, 2016). It should be noted that the consumption is often measured during optimal driving behaviour by the vehicle companies themselves.

PHEV		BEV	
Model	kWh/10 km	Model	kWh/10 km
MITSUBISHI OUTLANDER	2.4	TESLA MODEL S 85	1.7
VW PASSAT	2.0	NISSAN LEAF V1/V2	1.4
TOYOTA PRIUS PLUG-IN HYB	1.8	RENAULT KANGOO	1.3
VW GOLF GTE	1.7	RENAULT ZOE	1.0
VOLVO XC90 T8 TWIN ENGINE	2.1	NISSAN e-NV200	1.4

Table 1: Consumption per 10 km for the five most common PHEV and BEV models today. Source: PowerCircle (2016)

3.1.5 Charging behaviour

Due to the low penetration of EVs in the market today it is difficult to estimate human behaviour in terms of charging. Questions such as charging duration, location and power are important in the analysis of future grid impact. To answer these type of questions E.ON collected data from the the customers that own an EV today. The study showed that from the 384 unique EV owners roughly 82% of them were living in single family homes (E.ON, 2017). The survey also showed that the majority of customers charge their EV at home (see figure 8). It also showed that EV owners are typically families that are aware of the economical benefits of owning an EV. Recent studies in attitudes towards EVs also stated that the biggest public concern was the limited driving distance that current models provide (Circle, 2016).

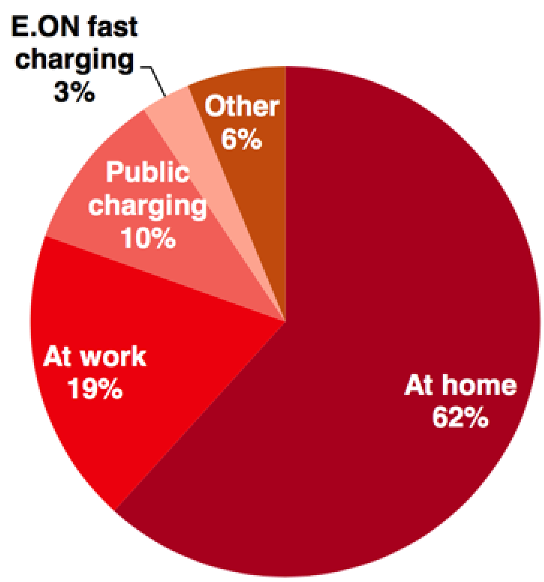


Figure 8: Response to the question "Where do you normally charge your e-car?" from 100 E.ON customers. Source: E.ON (2017)

In the analysis of possible power peaks the time of charging is crucial. Studies show that probable charging hours will be when people come home from work on weekdays (Grahn, 2013). These hours are already critical for the distribution grid and adding charging of EVs could have a major impact on the substation's power peak. Figure 9 display the hours when people start their everyday travels. It is clear that people start their trip back home from work around 17.00 on workdays. These numbers come from a large investigation made by the Swedish government agency for transport policy analysis (Trafikanalys, 2015).

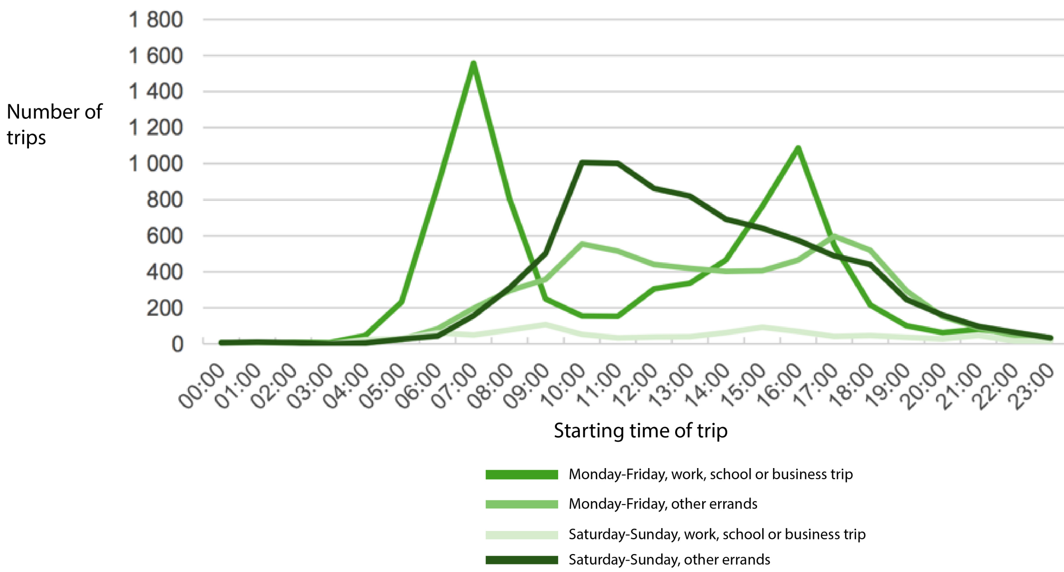


Figure 9: Display the time when people start their travels. Sorted according to type of trip and difference between weekends and weekdays. Source: (Trafikanalys, 2015)

3.1.6 Future prospects

Estimating how many EVs will exist in 2030 with a high level of accuracy is hard. The increase of EVs heavily relies on subsidies and financial incentives given by the government as well as environmental target goals. Also, the number of EVs will probably increase when they are more affordable due to lower production costs in the future. At this moment, Norway has the most EVs per capita. This is strongly correlated to its big upfront incentives when buying an EV, as seen in figure 10. Hence, an unsuspected bump in subsidies could cause a big overshoot to the estimates, and vice versa. It is noteworthy that, of the listed countries, Sweden has the lowest upfront incentive for BEVs. For PHEVs Sweden is somewhat around the median. This points to show that there should be margin for an increase in incentives if internal or external political pressure is applied. For instance, if Germany's ban on fossil driven vehicles passes, the consequent surge of BEVs would likely spread to neighbouring EU countries.

However, gatherings from several reports and studies point to that around 20% of all vehicles in Sweden will be electric in 2030 (Regeringskansliet, 2013)(Vattenfall, 2016). This is assuming some additional subsidies will be introduced, though nothing extraordinary. Different scenarios for when one million EVs (which correspond to 20% of todays vehicles) are reached can be seen in figure 11.

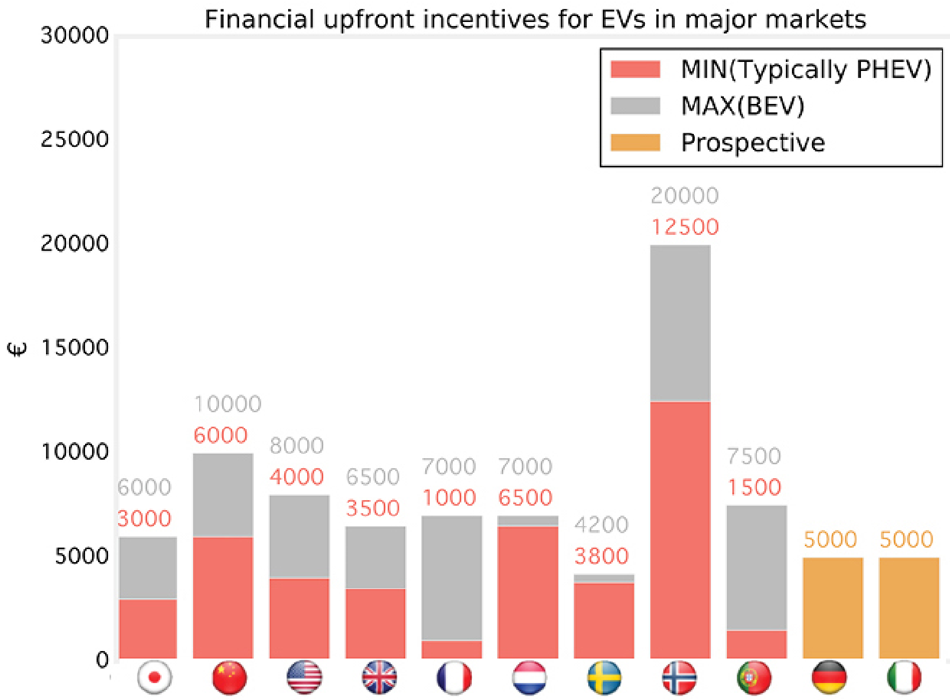


Figure 10: Financial upfront incentives of major markets in EU, America and Asia. Source: bain

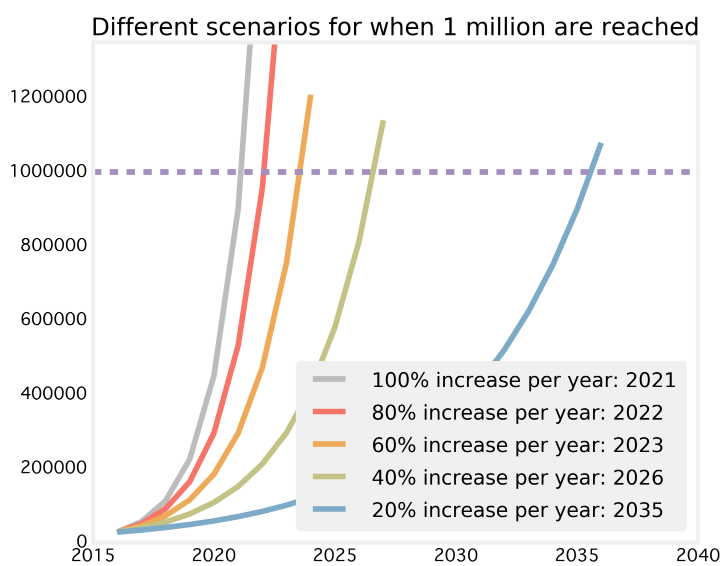


Figure 11: Different scenarios for when 1 million EVs are reached, which with today's number of vehicles is about 20%. Source: Circle (2016)

3.2 Challenges with the introduction of EVs

Electric vehicles will most likely cause larger power peaks in the grid. In the future, automatic control of charging will probably be implemented to charge smarter, but is disregarded in this report. That raises the question if the grid is dimensioned enough to handle a large scale introduction of EVs. Even though the substations in the distribution grid probably have margin to overloading today, the impact from EV charging should not be taken upon lightly. An electric vehicle has an electricity consumption of 3000 kWh per year which is equivalent to 15% of an electric heated household's yearly consumption (Örjan Larsson, 2010). This raises the concern about EV charging for grid owners, especially when charging will most likely occur during the most critical hours for the distribution grid. Earlier studies in this issue shows that a simultaneously charging of 1.3 million EVs would result in a combined power peak of 1300 MW (Montin et al., 2013). For comparison Sweden's power peak during winter 2014/4015 was 23 390 MW (SvK, 2015).

3.3 Photovoltaic systems PV

Since 2012 the installed PV capcity in Sweden has almost doubled each year. By the year-end of 2014 Sweden had a total PV installed capacity of 60 MW. From the installed capacity 54 MWh was produced which is equivalent to 0.04% of the total electricity production in Sweden (Energimyndigheten, 2015). During 2015 the PV installed capacity increased to 126 MW as can be seen in figure 13, which corresponds to 0.1% of the total Swedish electricity production.

The reasons behind the development of PV installations in Sweden are (IEA, 2015b):

- Falling system prices
- The government's direct capital subsidy for PV installations
- A general positive public opinion

The PV market has changed from off-grid PV to more grid-connected PVs and today grid-connected PVs holds 94% of the market (IEA, 2015b). The distribution of these PV systems have been spread throughout the country. Those municipalities that have had a strong development of PV systems are the ones that have had a high presence of PV organisations in that region. Recent studies also show that people who have adapted the technology have been strongly influenced by their neighbours and community (Palm, 2015). As seen in figure 12 municipalities in the north also have their share of PV systems despite its few sun hours during winter.

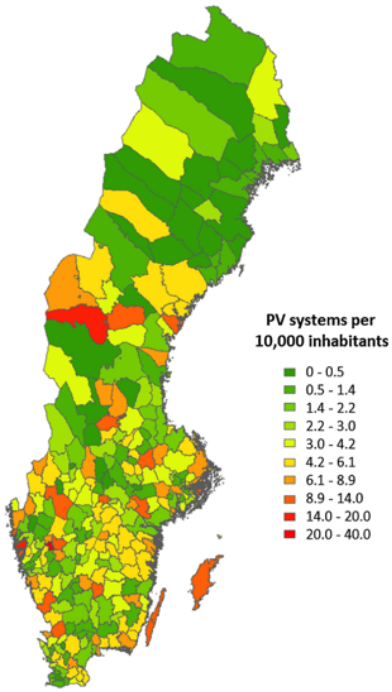


Figure 12: Distribution of PVs in Sweden. Source: Palm (2015)

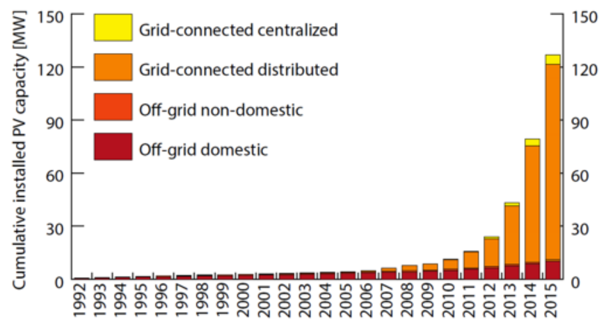


Figure 13: Sweden's total installed PV capacity. Source:IEA (2015b)

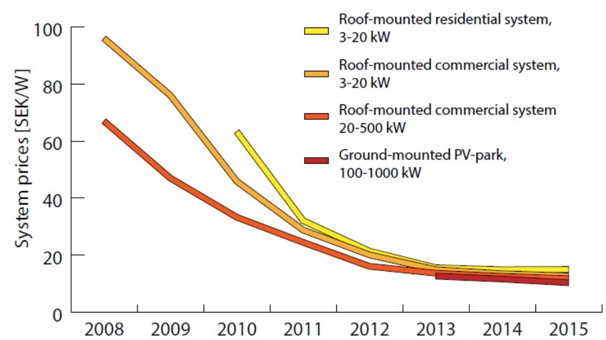


Figure 14: Price development for PV systems dependent on costumer type. Source: IEA (2015b)

The price of PV systems in Sweden has been rapidly decreasing since 2008. There are several explanations to this but major factors are increased competition between PV-companies, reduced equipment cost and the fact that purchases have gone up, creating steadier income for suppliers (IEA, 2015b). However there has been a slight slowdown recent years and the price 2015 were 6-8% less compared to 2014 which can be seen in figure 14. The price for PV systems depends on the type of costumer. In general, grid-connected PV systems for commercial costumers are less expensive. As an example a grid-connected roof mounted PVs in typically single-family homes have an average of 15.0 $SEK/W_{installed}$ were the same type of PV system for industrial and commercial buildings have only 11.8 $SEK/W_{installed}$.

3.3.1 Components and build-up

A PV system has two main parts: the array of PV modules and the current inverter. There is also an utility meter connected to the system. All of this can be seen in figure 15. When solar radiation strikes, the modules create a current through a chemical reaction that is transported to the inverter. The inverter changes the equivalent resistance in order to achieve a voltage level, corresponding to the maximum power that can be delivered by the modules. The utility meter measures difference between power generation and demand. A smart utility meter can then determine if power is to be exported or imported from the distribution grid (Nelson Sommerfeldt, 2016). Some PV systems include the usage of battery storage as a fourth part of the system. The battery's main function is to store power at high generation during low demand and vice versa discharge during low generation with high demand.

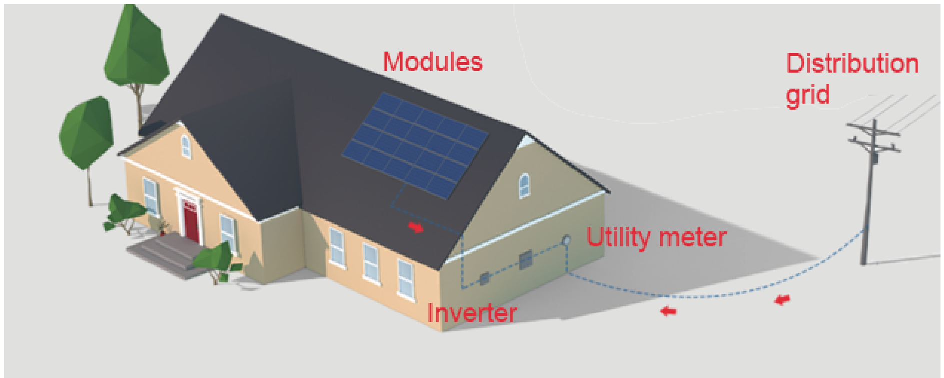


Figure 15: Household with PV system. Source: SolarCity (2016)

3.3.2 Future prospects

There is a strong development towards new technologies and concepts in the PV market. Recently the company of multi-billionaire Elon Musk, SolarCity launched their new concept solar roof which is modules covered with special glass, creating the appearance of a normal rooftop (see figure 16). There is also a wide variety of new materials for solar cells that are emerging the market. Common for these materials are higher efficiencies but naturally these materials also comes with currently higher production cost (Nelson Sommerfeldt, 2016).

Figure 16: SolarCity's solar roofs. Source: SolarCity (2016)

The future market penetration of PVs in Sweden will be influenced by several different aspects. In general Sweden's renewable electricity market is growing and the Swedish government recently stated that Sweden's energy production should by the year of 2040 be 100% renewable (Regeringen, 2016).

This means that the present 60 TWh of nuclear power that exist in the Swedish energy production must be replaced by either PV, wind, biofuels or hydroelectric energy. Even so, estimations made by the Swedish Energy Agency state that PV energy should by the year of 2040 only supply 5-10% of Sweden's electricity demand (Energimyndigheten, 2016a).

Although 5-10% would be a considerable step compared to today's share of PVs it is almost already achieved in other similar European countries (IEA, 2015a). As a comparison figure 17 displays the difference between other European countries and the world in total how much of the electricity demand that could be provided by the installed capacity of PVs today. The figure also states the country’s average irradiation which in practise says how many watt hours are obtained per year for each watt of installed capacity.

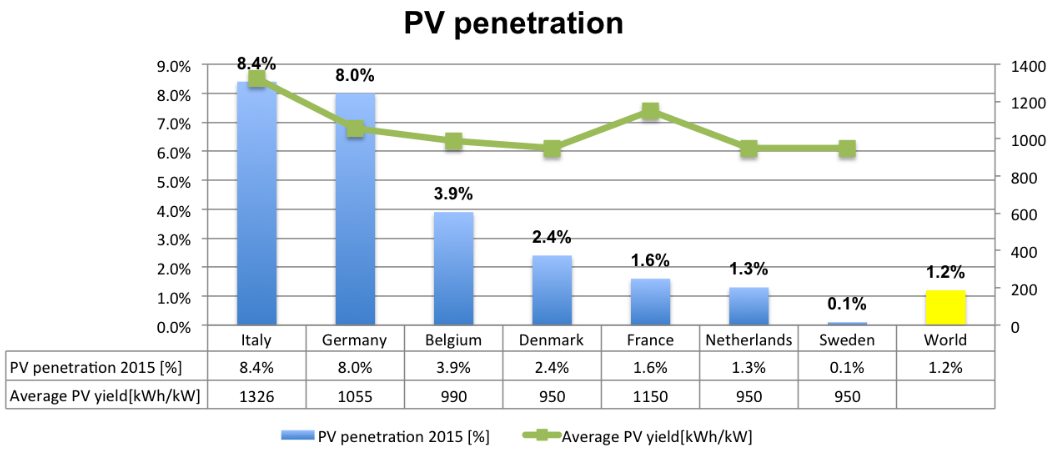


Figure 17: Share of the countries total electricity demand that can be provided by installed PV capacity, together with the country’s average irradiation. Source: IEA (2015a) Modified by authors.

4 The distribution grid and tariffs

In this chapter Sweden's power grid and its different levels are explained. This is followed by an introduction to the substation types that exist in the distribution grid and how transformer ratings are determined. Additionally some important aspects of power system analysis together with dimensioning guidelines are explained. Finally the structure and complexity of tariffs are described.

4.1 Sweden's power grid

Sweden's power grid is divided in three levels, see figure 18. Our study will only concern the low voltage distribution grid to which most of the fuse customers are connected (generally 63A and lower). This grid level is dominated by Vattenfall, Ellevio and E.ON Elnät, which together has about 50% of the market. These networks are natural monopolies and in each geographical area one company own the grid. Because of this, grid companies are highly regulated with limited freedom to set tariffs.

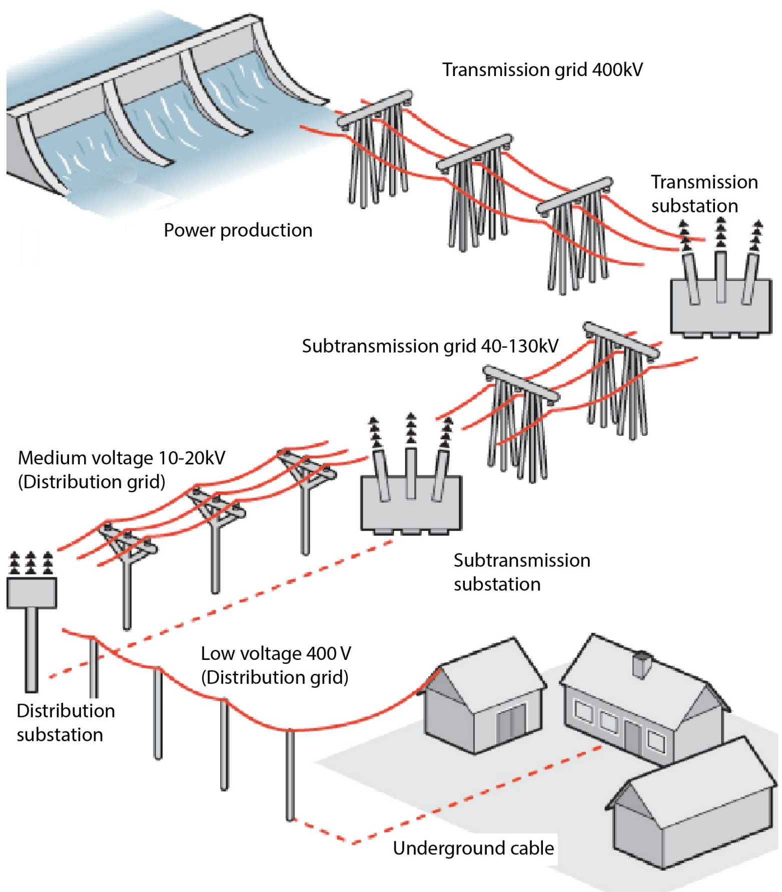


Figure 18: The structure of the Swedish power grid, with its three network levels. Source: Internal picture E.ON.

The three grid levels can be divided in to the following voltage intervals (energimarknadsbyrå, 2016):

- Transmission grid: 400-220kV
- Subtransmission grid: 130-40kV
- Distribution grid: Two levels, medium voltage: 30kV-10kV low voltage: 400 V

Each voltage level of the distribution grid is supplied by transformer stations that lower the voltage. For example a 130/40 kV transformer station lowers the voltage from 130 kV to 40 kV. The focus of this report is the transformers in the distribution grid which are addressed as secondary substations with rated power of up to 1600 kVA.

4.2 Substations in the distribution grid

E.ONs distribution grid consists of three different substations types: SS2, N3 and N8. The substation type SS2 has a transformer with a power rating up to 200 kVA and is therefore often used in the countryside. The type N3 has a maximum transformer rating of 315 kVA and is widely used in both countryside and commuter municipalities. N8 is a substation type mostly used in city areas or substations with a large number of customers connected. N8 has a maximum power rating of 800 kVA. N8 substations are also capable of having two transformers and can therefore consist of two 800 kVA when needed (Norrmontage, 2016). The substation types and their transformer power ratings are summarised in table 2.

Substation type	Transformer power ratings
SS2	50 - 200 kVA
N3	200 - 315 kVA
N8	315 - 800 kVA

Table 2: The capable power ratings for each substation type.

When building new substations, E.ON tries to estimate the consumption for its connected grid and often choose transformer and cables with large margin. One of the reasons for that is the low cost of equipment relative to the high cost of labour and excavation that is needed when constructing a grid, especially in urban areas.

For example, the cost of a 315 kVA transformer that is commonly used for the substation type N3 is roughly about 70 000 SEK, while a 500 kVA transformer has a price tag of roughly 90 000 SEK. The cost of constructing the actual substation, without the transformer, lie in the range of 220 000 - 260 000 SEK including labour cost (Energimarknadsinspektionen, 2014). Furthermore, building a substation in an urban area will likely increase that amount to almost 1 million SEK. Needless to say, the cost for a transformer with high power rating is sufficiently less than the material and labour cost for a substation. The labour cost for changing an existing transformer in a substation also comes with a great deal of costs. Therefore the transformer with the highest possible transformer rating is often chosen when designing distribution grids (Mireander, 2016).

4.3 Grid dimensioning

4.3.1 Apparent, active and reactive power

The power in a transformer is always measured in apparent power (kVA) which consist of both active and reactive power. Active power is the power that can be consumed and is measured in kilowatts. Reactive power is due to the phase angle between voltage and current that exist in an AC system and cannot do any actual work in terms of load. In power systems the power factor is used to calculate active power from apparent power. It is the cosine value of the phase angle between voltage and current, often written as $cos(\phi)$. To clarify, the power factor state how much useful energy that can be absorbed by the transformer, if the transformer have a apparent power rating of 315 kVA the active power rating is $315kVA * cos(\phi)$.

4.3.2 Thermal load

Every transformer has a rated load (kVA), voltage (V) and frequency (Hz). International standards state that transformers operated at their rated values should not exceed a temperature rise of more than 65°C above ambient (J. Duncan Glover and J.Overbye, 2012). When the transformer is operated at loads over its rating the temperature increases which shortens the transformer lifetime. If the transformer is located in substations with cooling equipment, the temperature could still be kept within limits and not damage the transformer, even when it is operating over its rating. The surrounding temperature will also cool the transformer which allow the transformer to operate at higher loads during winter.

4.3.3 Transformer utilisation factor

To analyse if a transformer is operating above its rating, an indicator such as transformer utilisation factor could be used. This factor is calculated as maximum measured power during a certain time period divided by the transformers rating, see equation 1 (PUCSL, 2014). The transformer utilisation factor declare how much capacity that is available in the grid during the highest peak load (Wigenborg, 2016). Therefore, it can be used in order to estimate if a transformer is in danger of operating near its rated values.

$$U = \frac{P_{max}}{C} \tag{1}$$

U = Transformer utilisation factor
P_{max} = Recorded peak load of transformer (in kVA) during reported period
C = Rated capacity of transformer (in kVA)

4.3.4 Voltage deviation

Voltage deviation is the difference between the voltage at a given point in the system and the nominal value, often expressed in percentage (Portal, 1999). It is mainly the reactance and resistance in cables that causes voltage deviation. Also the length and power supplied to the customers play a major role in the voltage received at the end-user (Ericsson, 1996). If voltage deviation would go as high as $\pm$ 10% electric equipment both in the power grid and at customers could be damaged. Also if voltage were to change in the mater of seconds, customers would notice light bolts twinkle, often referred to as "flicker" (PowerQuality, 2014).

4.3.5 Dimensioning guidelines

When building a new grid, E.ON has specified guidelines regarding dimensioning and margins (E.ON, 2016). For instance, when choosing a transformer for a grid in a developing area, expected peaks should not constitute more than 60% of the rating. In stagnant areas it's instead 90%. As time passes consumer behaviour changes (e.g. EV charging) or more customers connect to the transformer. This could cause the transformer to be loaded more than 100% of its rating. The predicament of when to upgrade doesn't have a clear cut answer. For example, if only one hour per year has a load that exceeds the rating it would not be upgraded. On the opposite, if during all hours the transformer was to run above its capacity it would definitely be upgraded. It is hard to determine a strict line between the two extremes and exactly when to upgrade. Overrunning to 140% of rated load in the winter might not be a problem at all due to cold ambient temperature. Also, overrunning consecutive hours is more severe than multiple one-hour occasions. Still, to give a general direction of how many substations need to upgraded, a limit of consecutive overrun hours as well as total overrun hours will be attempted to be set. These boundaries will come in intervals to highlight the uncertainty of the decision rules used.

E.ON also has dimensioning guidelines for voltages in the distribution grid. The same logic as in transformer loading applies here where a large deviation from the nominal voltage could have an effect on voltage quality. According to the standard SS-EN 50160 about voltage deviation in the power grid, voltage should not exceed $\pm$ 10% from its nominal value. E.ON has its limit on +6 % and -10% from of its nominal value for the whole distribution grid (E.ON, 2016).

4.4 Tariffs

In the analysis of future grid scenarios it is important not to forget how the grid companies' profit will be affected by the new development of EVs and PV systems. In order to have electricity available for every household every second of the year, grid companies must find a way to maintain grid quality in terms of voltage deviations and that demanded power can be supplied. With a clear change in the market from stable base production power to more unpredictable ones such as solar and wind (due to environmental factors), customers or grid companies may have to adapt in order to make the system work.

With the use of tariffs, grid companies have the possibility to change customer behaviour or secure enough income in order to maintain grid quality when for example PV systems do not produce. In general there is a large variety when it comes to how grid companies work with their tariffs. Like everything in the energy market tariffs are influenced by several different factors. In figure 19 there are some examples of factors, some more important than others, that could have an impact on the grid tariff. Grid companies are obliged to follow laws and regulations, such as the Electricity act. They also have to keep up with the new development of EVs and PV systems, while still making it easy for customers to understand what they are paying for. All these complex and important concerns make it difficult to design the perfect tariff. In terms of future tariffs, grid owners around Sweden are divided and there is an ongoing discussion on how the impact of PV systems and EVs should be accounted for. In general there are today three main types of fees included in the tariff: fuse, capacity and energy based fees.

4.4.1 The electricity act and the Swedish energy market inspectorate

The electricity act is one of the most important laws when it comes to tariffs. The law involves several sections that state how tariffs should be constructed. One important part of the act is that tariffs have to be constructed in a way that makes them accountable for the maintenance and investment needed for running the power grid. Another key part is that tariffs must be equal for all customers, in a certain customer group, and cannot be discriminating towards for example those who live in the countryside where cost for maintenance and development could be higher. Another consequence from the non-discriminating part is that customers who pay grid tariffs and electricity from the same company cannot in any way be favoured in forms of discounts.

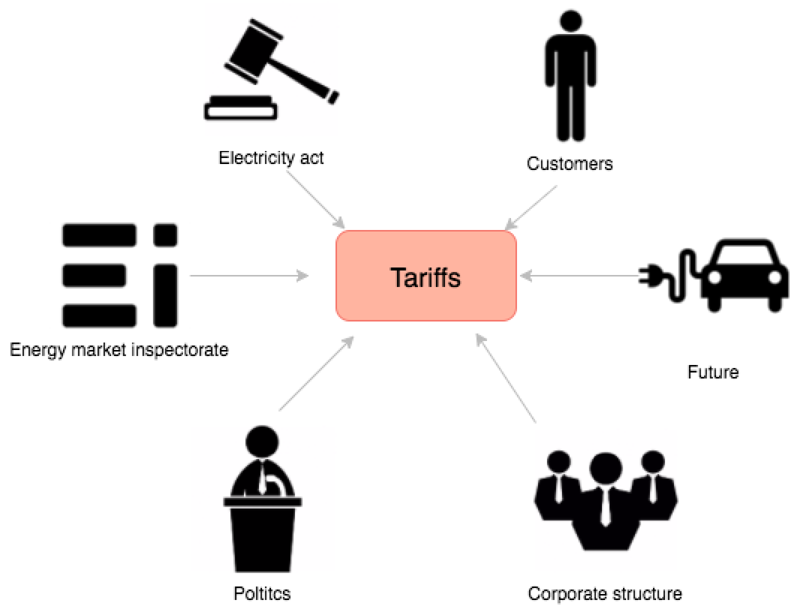


Figure 19: Possible factors influencing grid tariffs

The Swedish energy market inspectorate has the responsibility to make sure the grid companies act according to the electricity act. Another key part of the organisation's role is to set the revenue caps which state the allowed income grid companies can receive from customers (SvenskEnergi, 2016).

The revenue caps provide incentives for grid owners to construct grids with high efficiency and reduced peak loads, in other words lower the grid costs. The tariffs can then be used as a tool to reduce or move certain peak loads. The potential to move customer consumption from peak hours by the use of tariffs have been seen as a key factor in the future implementation of smart grids (Katzeff and Ramström, 2013).

4.4.2 Fuse-based fee

A simple fee that is based on the fuse used in households. The level of the fuse sets the billing terms where a higher fuse should reflect a higher consumption and therefore higher fee. This fee has been the most commonly used throughout history and is mainly used today to decide the fixed part of a tariff.

4.4.3 Capacity-based fee

The idea behind the capacity-based fee is to measure customer's peak consumption and set their electricity bill accordingly. For example power grid owners set the price per kilowatt where the customer will be billed according to its highest peak during the measured time period. The highest peak could either be the single highest peak or be calculated as the mean value of a certain amount of peaks during the measured period. Price per kilowatt can also be higher for peaks during certain hours when there is high stress on the grid. These kinds of fees are today commonly used for industries with high peak load. The main advantage with a capacity-based tariff is that it can provide incentives for customers to consume energy more evenly. An example is given to left in figure 20.

Capacity used in connection points between distribution grid and sub-transmission grid are priced in a similar manner. Here the distribution grid owner pays for a yearly subscription of capacity, meaning they set a max power limit beforehand rather than measuring highest peak of the year. If this limit is trespassed, fees for over running will apply. Both grids are oftentimes owned by E.ON themselves, but there are also cases where the sub-transmission grid are owned by another operator. These subscriptions are very optimised so that the distribution grid owner does not pay for too much capacity.

4.4.4 Energy-based fee

This is one of the most commonly used fees as the variable part of the tariff. With energy based fees the customer is charged according to their consumption in kilowatt-hours and the price per kilowatt can be set either yearly, monthly or even hourly. Compared to the capacity-based structure the energy-based does not necessarily provide incentives for the customer to flatten their consumption (Ek and Hallgren, 2012). Though, a hourly energy fee would possibly motivate the customers to move their consumption from peak hours when prices are high to less stressful hours. The hourly-based energy fees could in the future be directly reflected by the energy price on the Nord pool power market. An example of a time differentiated fee can be seen to the right in figure 20.

4.4.5 Tariff design

Tariffs are the price structures that the customers will be billed by. It is often a combination of the above mentioned fees. Most common for private customers is a variable energy-based fee together with a fixed fuse-based fee. For high consuming customers like industries, a capacity-based tariff is often used.

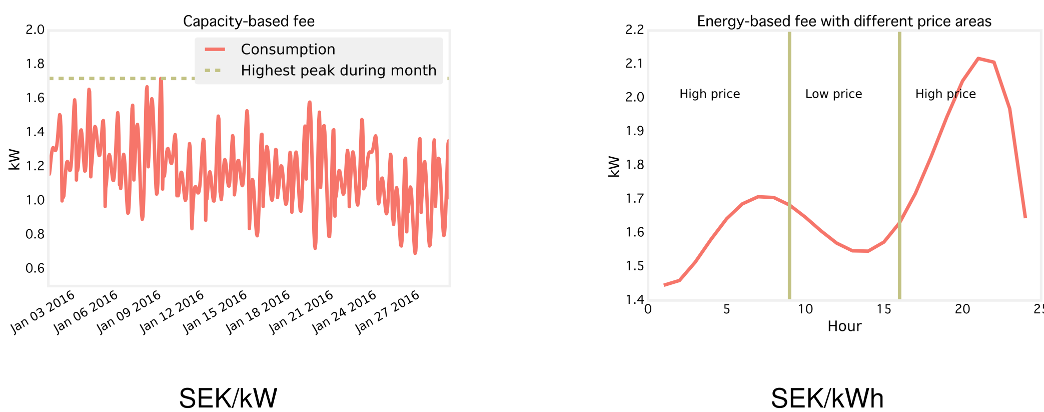


Figure 20: Illustration of different tariffs.

5 Future load behaviour and financial analysis

This chapter will explain our approach to handling big sets of available data in order to calculate the utilisation of the grid with and without EVs. Accessible data included customer consumption, substation ratings and vehicle statistics. Additionally, hourly measurements from 13 000 customers were used. The first step is doing a regression analysis on that data. This is followed by creation of consumption curves for all customers, using the yearly consumption from 1 million customers. Aggregation on substation level makes it possible to evaluate the current utilisation of the grid. To make the assumptions credible, validation is done by comparing to real substation data and weather conditions of that year. Electric vehicles are then modelled using statistics and then added onto the current consumption. Finally, annual revenues and costs are estimated to evaluate the current tariff structure. A summary of the described process is expressed in the flow chart in figure 21.

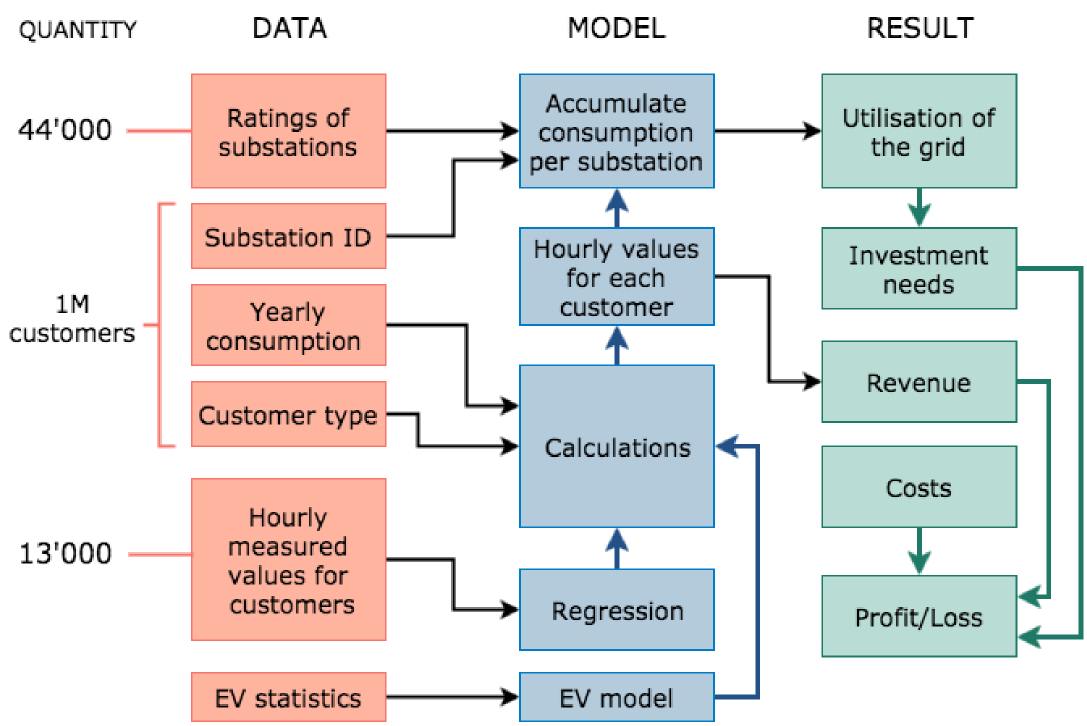


Figure 21: The analysis process.

5.1 Regression models

Regression analysis is a commonly used method in mathematical statistics for analysing if two or more variables are correlating. It can be used to determine the correlation between temperature and consumption. For example, the future consumption of a supermarket can be estimated (M.R Braum and BECK, 2014). Here it will be used for establishing the relation between power consumption and time. The regression analysis makes it possible to find trends and create general consumption curves using a small quantity of customer data.

5.1.1 Method

The basics of this method is using a certain number of real data points $Y = (y_1, y_2 \cdots y_n)$. In this case that is customer consumption in kWh/h from electricity meters with hourly readings. Together with a time vector with elements such as hours of day, days of a week or week of a year $X = (x_1, x_2 \cdots x_n)$, these two arrays can then be used as shown in equation 2 in order to find a relation between the two variables (Gunnar Blom, 2005), that is, how the consumption depends on time.

$$Y = \alpha + \beta_1 x + \beta_2 x^2 ... \beta_n x^n \tag{2}$$

Where $\alpha, \beta \cdots$ are regression coefficients. This can be expressed as:

$$Y = \beta X \tag{3}$$

Where the matrices are as follows:

$$\boldsymbol{Y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \boldsymbol{\beta} = \begin{bmatrix} \alpha_1 \\ \beta_1 \\ \vdots \\ \beta_n \end{bmatrix} \boldsymbol{X} = \begin{bmatrix} 1 & x_1 & x_1^2 & \cdots & x_1^n \\ 1 & x_2 & x_2^2 & \cdots & x_2^n \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_a & x_a^2 & \cdots & x_a^n \end{bmatrix} \tag{4}$$

By using equation 3 the regression coefficients can be estimated with equation 5 which is known as the least-square estimation method:

$$\beta^* = (X^t X)^{-1} X^t Y \tag{5}$$

The coefficients are often calculated using various computer programs. With the estimated regression coefficients β^*, estimated consumption can be calculated as $Y = (y_1^*, y_2^* \cdots y_n^*)$ by using the X matrix. Figure 22 shows an example of a second order polynomial regression fit to scattered data.

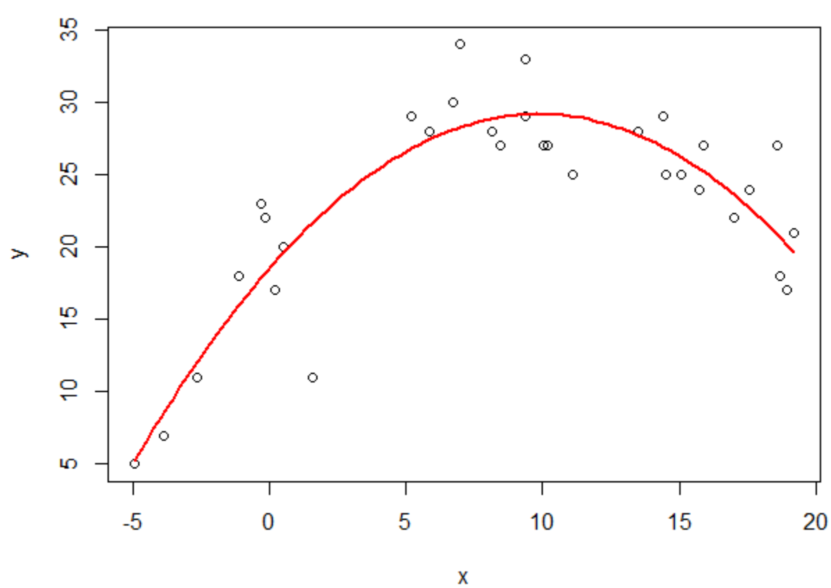


Figure 22: Example of a regression of 2nd order.

5.2 Creation of estimated consumption curves

E.ON does not have hourly measurements on all of their (fuse) customers - only a fraction of them. To perform load calculations with regard to the entire power grid would require data on all customers. Therefore, estimated hourly values for each customer are calculated. Fortunately, the measured values that do exist are spanning across multiple customer types such as single-family homes, apartments, small industries, commerce etc. The data available for each customer type can be used to create a general model of the consumption behaviour throughout the year. This is more commonly called *profile curves*. These curves describe the average normalised yearly consumption profile of a customer type, consisting of 8736 values[1] with one value for each hour of the year.

5.2.1 Sorting and preparing data

As can be seen in fig 21, data from a large variety of sources were collected and used in the process to generate theoretical hourly values. The following data was collected and available for every customer:

- Yearly consumption
- Supplying substation
- Type (house, apartment...)
- Municipality

For roughly 13 000 customers meter readings of hourly consumption were available. These customers were sorted into different categories. A category reflects what type of customer it is, its geographical position and type of heating. The geographical zones are declared in figure 23.

For all customer types, there was one profile for each zone such as: *south:apartment*, *north:apartment*, *south:house* etc. Furthermore, the type *house* was split into *south:house:heating* and *south:house:no_heating*, where the first denotes electrical heating and the latter a household where heating does not depend on electricity. To keep the model as simple as possible, temperature was not a variable in the regression. Though, the use of categories based on zones does account for outdoor temperature differences within the country. Finally, for each hour, all values in a category are averaged so that all categories have an average consumption profile for one year. There were 11 customer types, but the majority of the customers belonged to one of these six:

- House (Single family home)
- Apartment
- Commerce
- Industry
- Holiday house
- Agriculture

[1] A year has 8760 hours, however, data was missing for one day and therefore only 8736 values were used.

These 11 types together with the 4 geographical zones result in 44 different categories.

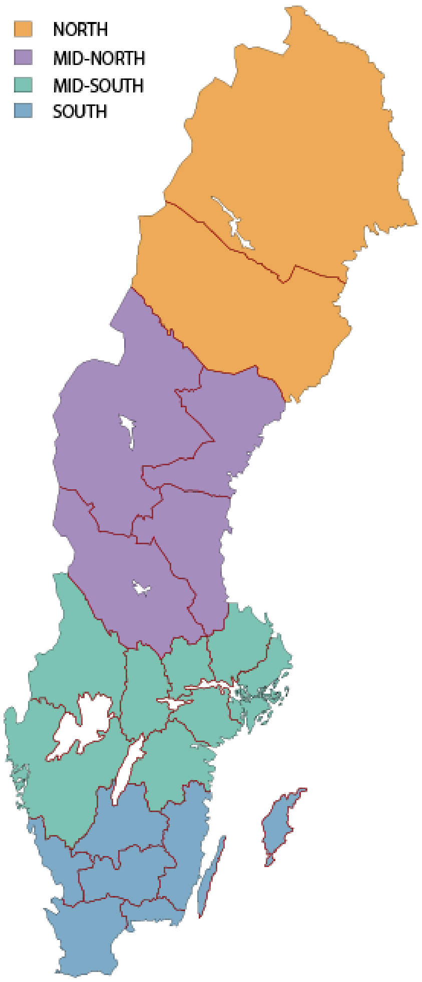


Figure 23: The four zones the regression was based on.

5.2.2 Multi-variable regression

Once each category has a profile curve that represents the average consumption for customers belonging to it, the regression analysis can begin. Regression will be performed on the data in three time scopes to account for different factors, as listed below. It was also normalised, meaning each value was converted to a percentage of total.

1. A profile for the entire year, one value for each week, to represent temperature influence
2. A profile for each week, consisting of one value for each day, to register the difference between weekdays and the weekend
3. Separate profiles for each day of the year, consisting of one value for each hour, to represent intra-day consumption patterns

The data was aggregated in the three time frames described above. When aggregating values per week for instance, the result is 52 values each denoting its percentage of yearly total.

That would be the X matrix as described in *Regression models*. Then for each time frame the regression coefficients, β^*, of the fifth order were calculated using the least square method. This resulted in estimated consumptions for each time frame. For instance, weekly values were given according to equation 6.

$$Y^* = (week_1^*, week_2^* \cdots week_{52}^*) \tag{6}$$

After regression on all time frames are made, iterating over each week, day and hour and multiplying each percentage results in 8736 normalised values. A fictive example of this is given in equation 7. Here the normalised value of the consumption 8 am on a Monday the first week of the year is calculated. In the example, 3% of the yearly consumption is consumed in the first week of January. Similarly, Monday's consumption constitutes 14% of that weeks' total. Finally, between 8am and 9 am, 7% of daily total is consumed.

$$Perc_{specifichour} = WEEK1_{perc} * MONDAY_{perc} * TIME8am_{perc} = 3\% * 14\% * 7\% = 0.03\% \tag{7}$$

If total yearly consumption is multiplied with 0.03%, the consumption during the specified hour is calculated. Example of this for a household with a yearly consumption of 15 000 kWh is given in equation 8.

$$Perc_{specifichour} * Consumption_{year} = 0.03\% * 15000kWh = 4.5kWh \tag{8}$$

As stated, doing this for all hours of the year yields the estimated consumption curve. The results of this can be seen for a household located in south of Sweden with electrical heating in figure 24. In figure 25 the consumption of an industry in south of Sweden is illustrated.

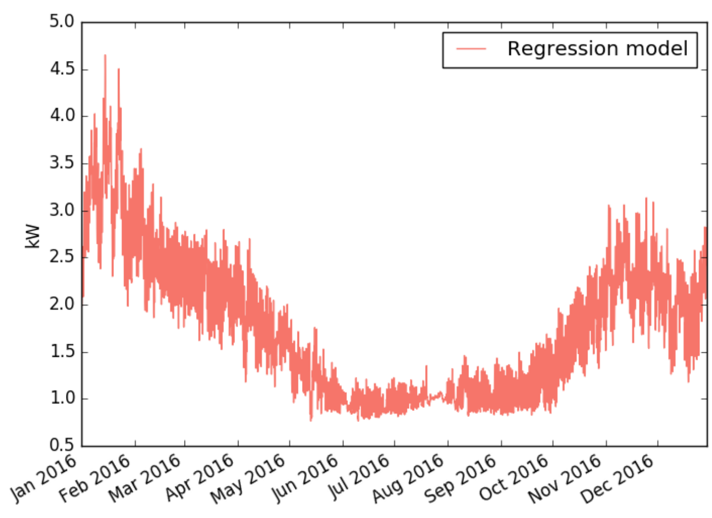


Figure 24: Profile from regression of the average consumptions in kWh/h for the category SOUTH:HOUSE_HEAT.

Figure 25: Regression of the average consumption for the category SOUTH:INDUSTRY.

5.2.3 Aggregation on substation level

To receive hourly values for a customer, its yearly consumption is simply multiplied with its category's normalised profile curve. This is done for all fuse customers connected to the distribution grid. When aggregating all customers on a substation level, a consumption curve for each substation is received. Across the grid, losses are expected to be 4% on average (Leisse, 2016). This means that every transformer rating were multiplied by a factor of 0.96.

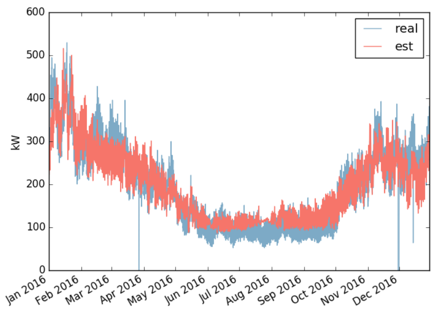
There is one caveat: substations with 4 or less connected customers have been ignored in the calculations. These transformers were almost exclusively below 50 kVA, small substations that is. Of the total 44 000 transformers, roughly 14 000 were skipped because of this. This is due to the fact that our model is largely based on averaging, thus tending to be inaccurate in too small scopes. Also, it is hard to distribute EVs correctly if there are to few customers. The skipped substations were of course excluded from the financial analysis.

5.3 Validation of consumption curves

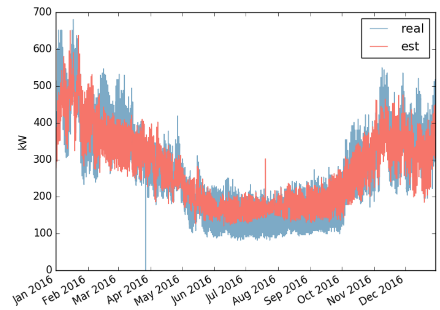
When calculating these curves, which are based on regression, it is of course necessary to validate the results. Secondary substations with hourly read electricity meters are uncommon, but 11 stations had hourly measurements available. Some of those were not used due to the fact that connected customers in reality were more than our data stated. This left 6 stations that had the same amount of customers as our data. Across the whole data set, 0.11 customers were missing per substation on average. That means that about 0.5% of all customers in our data did not have a specified connected substation. These customers did not have a fuse specified, which leads us to believe they were power debited customers.

5.3.1 Comparing with real measured substation hourly values

Comparing highest power peak between estimated and actual consumptions resulted in an average error difference of 4.2% on the 6 stations that was validated against. Real data and estimated data of a substation are plotted in figure 26. Worth noting is that the peaks oftentimes do not occur simultaneously, however seem to be of the same magnitude. Since it's the magnitude that affects dimensioning, accuracy is wanted in this rather than in when it occurs.



Substation N000962

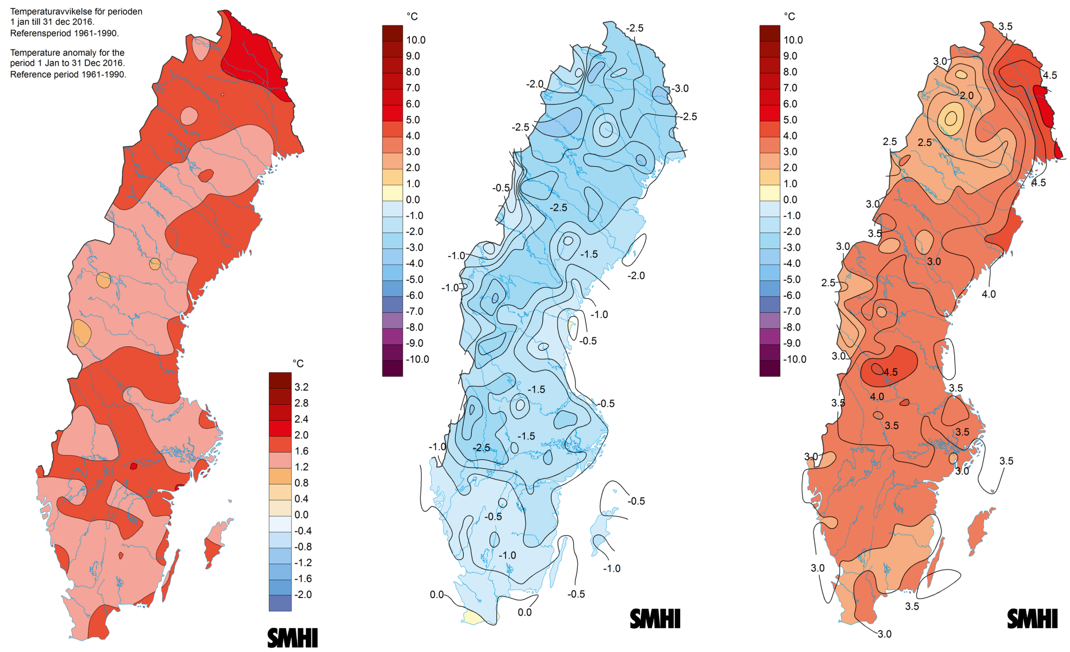


Substation N000730

Figure 26: Comparison between estimated and real hourly data. The blue graph drops to zero sometimes due to missing data.

5.3.2 Weather impact

The data set used when creating profiles as well as the yearly consumptions were from the time period Dec 2015 to Nov 2016. Since grid stress is closely correlated to outside temperature, it is important to see if this period was warmer than usual or not. The Swedish Meteorological and Hydrological Institute (SMHI) measures the average temperature for Sweden each year in great detail. It can be seen in figure 27 that January was slightly colder than average whereas February was significantly warmer. This will be discussed further in the *Discussion* chapter.



2016 January 2016 February 2016

Figure 27: Difference between mean temperature for given case and mean temperature for time period 1960-1990.

5.4 EV market penetration cases

Based on the studies made in *Chapter 3 - EV and PV overview*, the following analysis was divided into three cases of EV market penetration. For all cases it was assumed that the total amount of vehicles remains the same as today. The values represent a percentage of total vehicles, that is, the EV market penetration.

- Today
- Base case - 20% EVs
- High case - 40% EVs

It should be noted that EVs were only distributed amongst single family homes in this study. The goal is to target unexpected charging that E.ON cannot easily foresee. It is believed that the other types, as for instance apartment blocks, will contact E.ON before installing charging posts in their entire parking lot - giving E.ON the opportunity to evaluate the load situation.

5.5 EV charging model

In order to calculate the impact from EVs a charging model was created. The model is based on data from the SCB (Statistiska Centralbyrån), technical reports about expected charging behaviour and finally assumptions made together with employees at E.ON involving mathematical statistics. Figure 28 displays the information that has been taken from each segment.

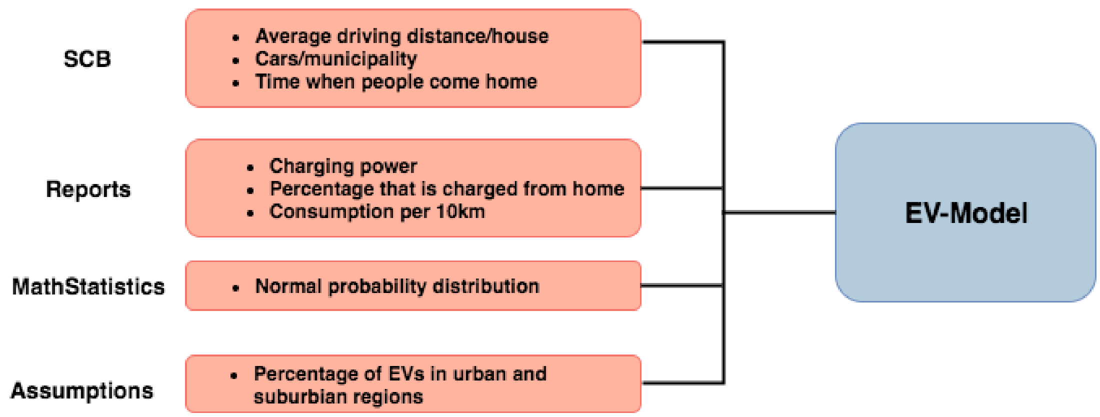


Figure 28: EV model inputs

5.5.1 Charging time

From chapter *3.1 - Electric Vehicles* consumption per 10km for the most popular PHEV and BEV were stated. Because of the fact that the numbers came from the car companies and are usually measured during optimal driving situations a general consumption of 2 kWh per 10 km was assumed for all EVs. This is slightly higher than for most of the BEVs and a little bit less then for the PHEVs. A charging power of 3.7 kW was assumed for all vehicles. This charging power can be achieved for any household today without having to upgrade fuse.

SCB is the largest statistic agency in Sweden which publishes statistics on everything from childbirth to average income per municipality. Every third year, a report is published about Swedish travel habits. The report includes statistics about average travel distance for 10 different classifications of municipalities (metropolitan municipalities, commuter municipalities etc.) made by SALAR (Swedish Association of Local Authorities and Regions). SALAR has a list that categorises every municipality according to these 10 classes, combine it with the report and it results in a list with average travel distance per day and person for every municipality in Sweden.

This list combined with the SCB data about average people per household, for each municipality, result in a travel distance per household, see figure 29. This information together with a charging power of 3.7 kW and a consumption of 2 kWh/10km result in a average *charging duration* for a single-family home per municipality. With the results from the EV survey made by E.ON it was assumed that only 60 % of the total travelling distance was charged from home.

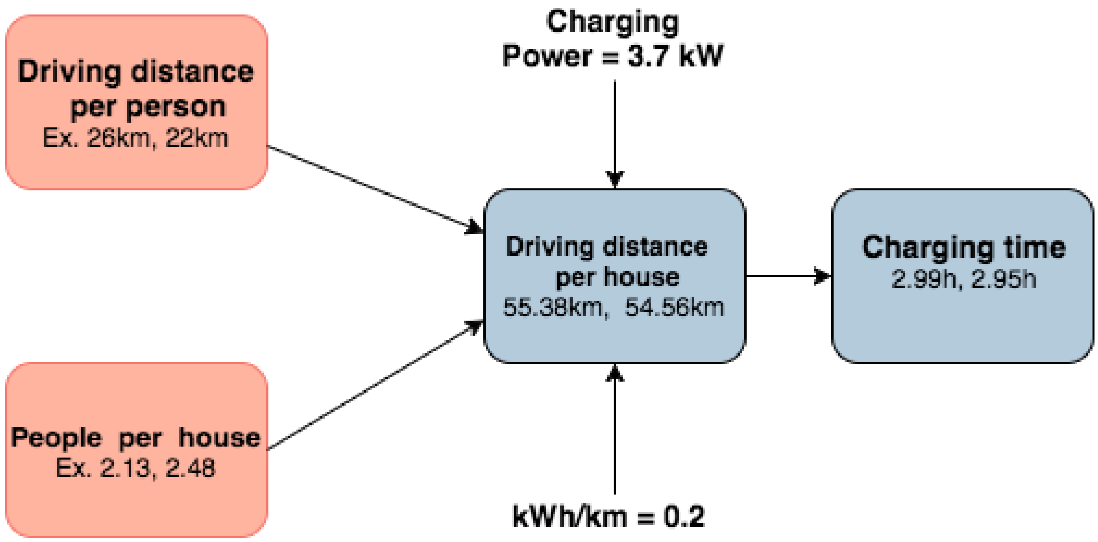


Figure 29: How charging time for each municipality was calculated

5.5.2 Geographical distribution of EVs

Estimations were made regarding how the distribution between EVs will differ in urbanised areas from the countryside. It was assumed that the penetration of EVs in urban municipalities would be more than twice as much as in other areas. In order to still have 20% respectively 40% EVs of total cars in 2030 they were distributed according to table 3. This was done with information about the current distribution of cars for SALARs municipality categorises taken from SCB.

Percentage of cars that will be EVs		
Case	Base case	High case
Urban regions		
Metropolitan municipalities	35%	70%
Suburban municipalities	35%	70 %
Suburban regions		
All other municipalities	15%	30%
Total percentage of EVs	**20 %**	**40 %**

Table 3: How the EVs were distributed between SALARs municipality categories

5.5.3 When charging occurs

With the reports mentioned in *Chapter 3 - EV and PV overview* it is reasonable to assume that home-charging will probably occur in the evening when people come home from work. To model this behaviour the normal distribution model was used with an expected arrival time home with a mean value of 18.00 and a standard deviation of 45 min. From the normal distribution, a person's arrival time home from work, was randomly generated. For simplicity, it was assumed that the person immediately plugged in their EV and started charging.

5.5.4 Summary of EV model

In table 4 all the parameters of the EV-model are stated. Regarding how long people charge their EV the statistics show that it was 2-3 hours for all the municipalities. Due to the lack of shorter time steps than hourly values for consumption, an average of three hours was assumed for every municipality. For simplicity, the model was applied for every day of the week and did not take in to consideration if people did not go to work on weekends. To clarify, during weekends it was assumed that the charging behaviour was the same as for workdays. Figure 30 shows an illustration how the model works, with 50 people charging their EV according to their time home from work.

Charging power	3.7 kW
Consumption	2 kWh/10 km
Mean arrival time home from work	18.00
Standard deviation(SD)	45 min
Percentage of total driving distance that is charged from home	60 %
Charging duration	3 hours

Table 4: Summary of EV-model

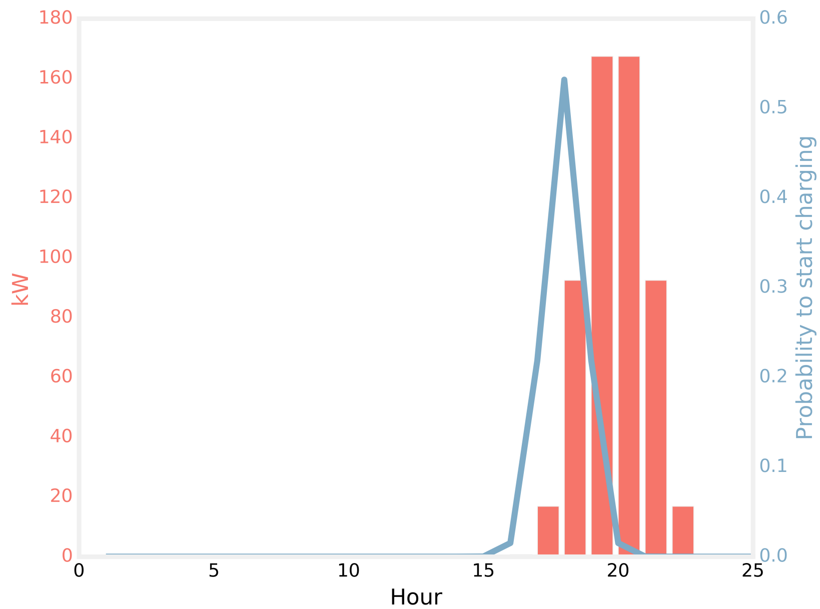


Figure 30: Illustration of 50 people charging their BEVs with 3.7 kW, mean = 18.00, SD = 45 min. The blue plot represents the normal probability distribution for when people get home from work, and therefore start charging.

5.6 Calculating utilisation factor

Adding EV-charging on top of existing consumption for a portion of the customers results in new consumption curves for each substation. These will naturally have larger power peaks than they had with no EVs. The utilisation factor for each station was then calculated for three cases of EV market penetration: today, 20 and 40 percent. When calculating the utilisation rate, $\cos(\phi) = 0.9$ was used (see equation 9).

$$U = \frac{P_{max}}{C * \cos(\phi)} \tag{9}$$

U = Transformer utilisation factor
P_{max} = Recorded Peak Load of Transformer (in kW) during reported period
C = Rated capacity of Transformer (in kVA)
$\cos(\phi)$ = Power factor = 0.9

5.7 Estimating investment needs in the distribution grid

Decision boundaries for when to upgrade a substation can be seen in table 5 below. If a transformer is overrun according to the specified boundaries, it needs to be upgraded. When deciding which rating is needed, maximum peak power during the year is used as base. As explained in *Chapter 4 - The distribution grid and tariffs*, the maximum power peak should constitute not more than 60% of the new rating.

	More restrictive limits		Less restrictive limit	
	Sequentially	Yearly total	In a row	Yearly total
100%-120%	24	250	48	500
120%-140%	12	100	24	200
>140%	6	25	12	50

Table 5: Conditions for upgrading a transformer based on overload hours.

If a substation was in need of a new transformer, the current substation type was taken in to account to analyse if the station itself was in need of an upgrade. The types listed in chapter *4.2 Substations in the distribution grid* had certain transformer power ratings which were used to analyse which substation type was needed for the new transformer. If the substation could hold the new transformer the investment for that station was only for the new transformer. In the same way if the substation was unable to hold the new transformer the investment for the the new substation was also included. These numbers were taken from norm values set by the Swedish energy market inspectorate and are stated in *Appendix - C* (Energimarknadsinspektionen, 2014).

5.8 Estimating revenue and cost

The standard tariff is based on fuse size(maximum power) and consumption in kWh. There will be an increase in consumed energy in terms of kWh, but there will also be instances where the customer has to upgrade its fuse.

5.8.1 Revenue from charging energy

First off, the total amount of kWh that will be needed for charging had to be determined. This was already known from previous steps, but the charging amount also had to be sorted based on fuse and geographical zone of the household. This is to match the price categories in EON's tariff list. Multiplications between the kWh accumulated in each price category and respective prices (see *Appendix - A*) was then made. Summing up all rows yields a revenue of 63 MSEK plus taxes in additional revenue in the case of 20% EVs, and roughly twice as much with 40%.

5.8.2 Revenue from fuse upgrades

The increase in terms of larger power peaks across the customers will generate revenue due to fuse upgrades. Equation 10 describes an estimation of max phase current. It is assumed that the customer's load is balanced before EV charging begins. Taking the power before charging begins and dividing by 3 yields power per phase. Then, by adding EV charging to one phase, that phase's max power is received. Dividing with phase voltage results in the max phase current. One phase is used for normal charging (3.7 kW), as is described in *EV and PV overview*.

$$I_{phase,max} = \frac{\frac{P_{before}}{3} + P_{charge}}{U_{phase}} \tag{10}$$

Where:
$I_{phase,max}$ = New maximum current
P_{before} = kWh/h before adding charging
P_{charge} = Charging power
U_{phase} = Phase voltage

If $I_{max} > 1.1 * I_{fuse}$ that customer will probably have to upgrade to a fuse that can handle the new max current[2]. This was checked for all customers. If the condition was true, the extra cost for that specific customer to upgrade its fuse was added to a total sum. This was done for 20% EVs as well as 40%, and the results can be seen in table 6. Example calculations can be seen in *Appendix - A*.

EV penetration	Affected customers	Revenue increase
20%	54 495	250 MSEK
40%	109 231	512 MSEK

Table 6: Increased income due to upgrades of fuses

5.8.3 Subscription fee to sub-transmission grid

Adding all increases in power due to charging across the entire distribution grid results in an additional 269 MW (20% EVs), as can be seen in *Appendix - A*. This would, at a weighted price $375\frac{SEK}{kW}$ (Internal price list towards sub-transmission grid) result in subscription fees of $269*10^3kW*375\frac{SEK}{kW} = 101MSEK$. A market penetration of 40% EVs will cause an increase of 545 MW, which by the same logic would cost 205 MSEK.

[2]Customers might instead contact an electrician to re-balance the phases. This is extremely hard to estimate however, and is therefore disregarded.

5.8.4 Investment costs in the distribution grid

Given earlier stated conditions for overload, investment needs for 20% EVs will lie in the range of 2.3 MSEK to 4.5 MSEK. For 40% a threshold seems to have been passed and investment lies in the range of 12.3 MSEK to 25.9 MSEK. It should be noted that this is a one time investment with an economical lifespan of 40 years. To calculate yearly cost the annuity method will be used, as seen in equation 11. The cost of capital in the industry is commonly chosen as 4.53%. The annuity factor k is then multiplied with the investment sum to calculate the yearly cost, as presented in table 8.

$$k = \frac{p}{1-(1+k)^{-n}} = \frac{0.0453}{1-1.0453^{-40}} = 5.18\% \tag{11}$$

Where:
k = annuity factor
p = cost of capital
n = economical lifespan (years)

	More restrictive limits	Less restrictive limits
20%	4.5 MSEK	2.3 MSEK
40%	25.9 MSEK	12.3 MSEK

Table 7: Upgrade costs based on boundaries specified in table 5

	More restrictive limits	Less restrictive limits
20%	0.2 MSEK/y	0.1 MSEK/y
40%	1.3 MSEK/y	0.6 MSEK/y

Table 8: Upgrade costs on a yearly basis, based on 40 year economical lifespan and a cost of capital of 4.53%

5.9 Result

Figure 31 shows the utilisation factor for the substations in the distribution grid. They are grouped up in the intervals *Low*, *Normal*, *High* and *Overload*. The interval limits are based on E.ON's dimensioning guidelines and are clarified in table 9. For example, today 83.5% of the substations have a low utilisation factor, meaning $U < 0.6$. As expected the amount of overruns increases slightly when adding more EVs into the mix.

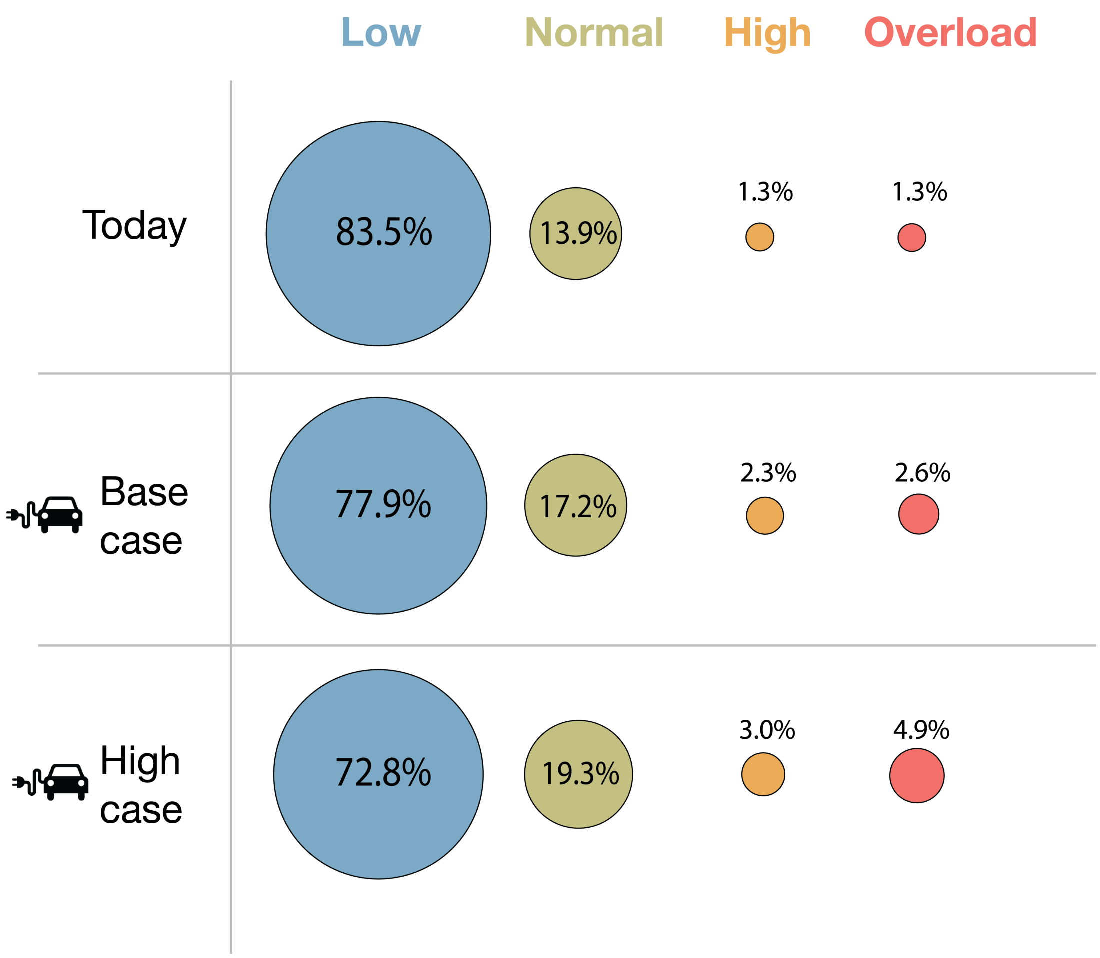


Figure 31: Utilisation factor = $\frac{P_{max}}{C*\cos(\phi)}$ for the substations in the distribution grid. The areas of the circles are proportional to their respective percentage. Where low =0-59%, medium = 60-89%, high = 90-100% and overload =>100%

Label	utilisation factor
Low	0%-59%
Normal	60%-89%
High	90%-100%
Overrun	> 100%

Table 9: Intervals used when presenting load situation in the distribution grid.

The result from the financial analysis can be seen in table 32. In both cases, the profit far exceeds the cost and the results are 213 MSEK and 430 MSEK for 20% and 40% EVs respectively.

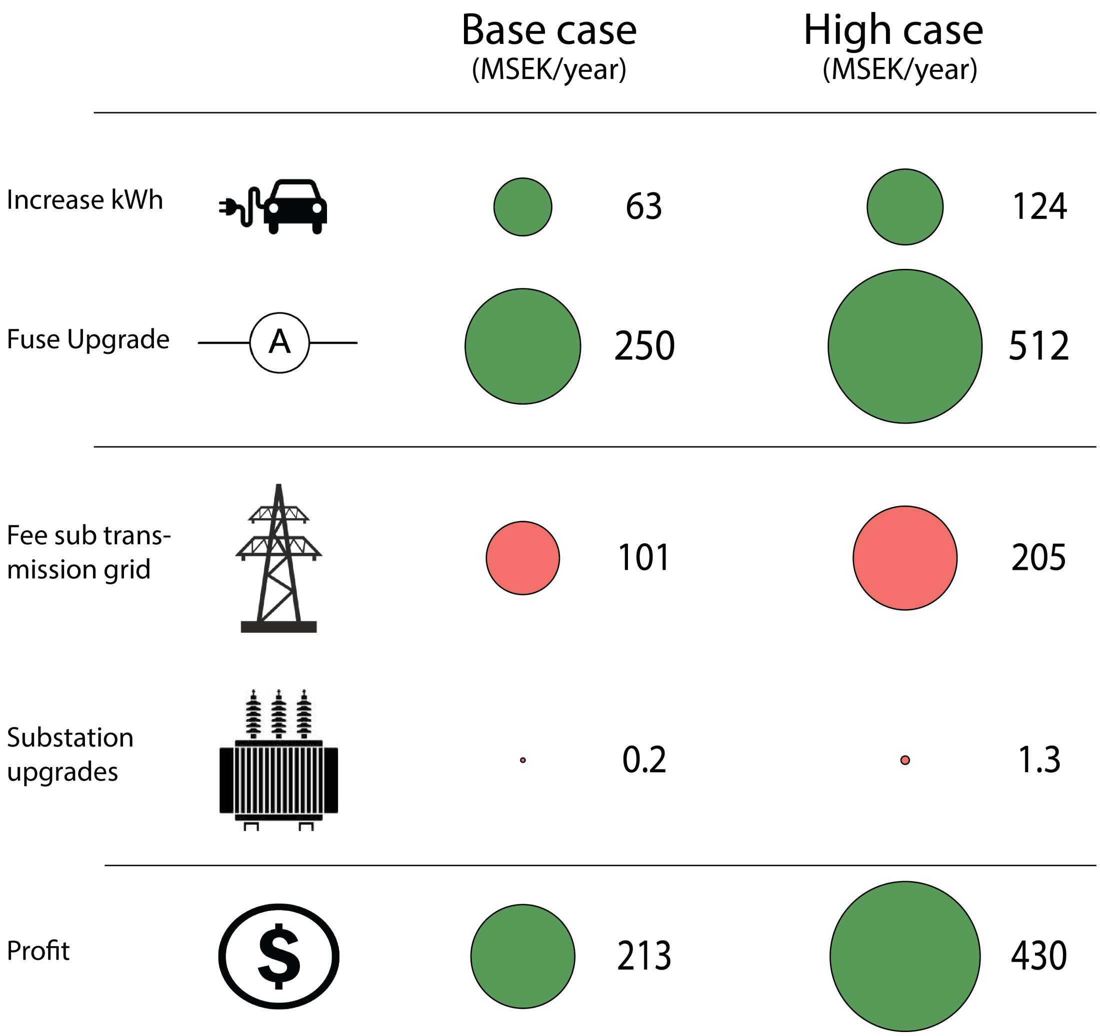


Figure 32: A summary of the revenue and cost from EV charging in the distribution grid. The green circles represent revenue whereas the red represents cost. The areas of the circles are proportional in size to the circle area for fuse upgrade 512 MSEK. All figures are in MSEK.

6 Case study in a stressed grid

From *Chapter 5 - Future load behaviour and financial analysis* certain substations had high utilisation factors. In order to analyse the possible impact from EVs further, one of the substations was designed and analysed using a power system simulation software. In this case study, PV systems are also included to see the effects. In *Chapter 5 - Future load behaviour and financial analysis* the substation had a transformer utilisation factor over 100%. This substation is located near Stockholm and is classified as a "Suburban municipality to a large city" according to SALAR. The grid is perfect for the goal of our study, since all customers are single family homes and are therefore potential EV and PV owners. The selected substation and its connected grid was modelled using the software DPG.Sim academic. Grid and customer information was taken from E.ONs software's dpPower and SAP. Technical guidelines regarding voltage deviation and loading limits were obtained from E.ON employees in the distribution grid department. The customer loads calculated from were also used for this case study. In this chapter the methodology for the simulation together with the actual results are presented.

6.1 Grid description and build-up

The substation is located in Järfälla near Stockholm and consists of 35 customers, all of them potential EV owners. The grid has 77 cable sections, 8 electric cabinets and one 300 kVA transformer. The fuses used for the customers were in the range of 16-25 A which are standard for Swedish houses. All households use electricity for heating which indicate a relatively high consumption. The voltage levels were 11kV on the high voltage side of the transformer and 0.4 kV on the low side. The feeding 11kV network was modelled as a slack bus on the 11kV voltage side with nominal voltage 1 p.u and operational angle 0 degrees. A summary of the grid data is displayed in table 10. Figure 33 displays the number of customers that were connected to each branch of the grid.

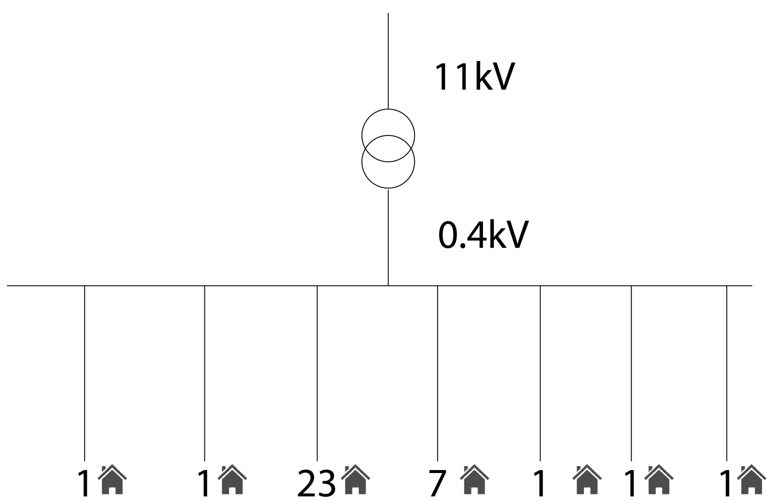


Figure 33: Shows how many customers who were connected to each branch of the grid in Järfälla. The voltages at each side of the transformer are also displayed.

Grid data	
Substation	"Järfälla" - GT3261J
Transformer rating	300 kVA
Single-family homes	35
Cables	77
Electric cabinets	8
Joints	28
Fuses	16-25 A
Heating source	Electricity
Yearly consumption per household	12,000 - 42,000 kWh

Table 10: Grid data overview.

The grid in Järfälla consists of 77 different cables, all of them underground cables. The cables were listed in dpPower, together with information about the dimensions of the cables. Capacitance for each type of cable was calculated using equation 12 with uF/km, each cable also had a listed maximum current (Ericsson, 1996).

$$Shunt\_capacitance[\mu F]_{cable} = \frac{\mu F}{km} * length[km]_{cable} \tag{12}$$

In dpPower the resistance and reactance in each point are stated as Thévenin impedance. For example the customer had certain reactance and resistance figures which were different from the joint before or any other connection point. These values could be used to calculate resistance and reactance in every cable (see equation 13 and 14). Shunt capacitance, reactance and resistance were all used as cable input values in DPG.Sim.

$$Reactance[\Omega]_{cable} = Reactance_{After} - Reactance_{Before} \tag{13}$$

$$Resistance[\Omega]_{cable} = Resistance_{After} - Resistance_{Before} \tag{14}$$

For the 300 kVA transformer copper losses and short circuit voltage was needed. Unfortunately E.ON no longer has specifications about the 300 kVA transformers. Therefore a 315 kVA transformer technical specifications were used (*see Appendix* - *B*). The transformer parameters used for the simulations are stated in table 11.

Transformer parameters	
Rated power	300 kVA
Short circuit voltage $U_k(\%)$	4.11%
Coppar losses $U_r(\%)$	0.875 %
Turns ratio	11/0.4 kV

Table 11: Transformer parameters

6.2 Scenarios

Five different scenarios were used in this simulation. Three with different penetration of EVs and two with a high penetration of EVs and PV systems to analyse if PVs could reduce the high peaks developed by EVs. The scenarios are summarised in figure 34. As stated in *Chapter 5.5 - EV charging model* certain areas were more likely to have a higher penetration of EVs. The municipality Järfälla was one of them and therefore simulations were made with

35% and 70% EVs. The same EV charging model described in *Chapter 5.5 - EV charging model* was also used in this case study. The PV capacity for the whole grid was assumed to be 20kW installed in the first case and 52 kW in the second. For both PV cases, the PV systems were randomly distributed within the grid.

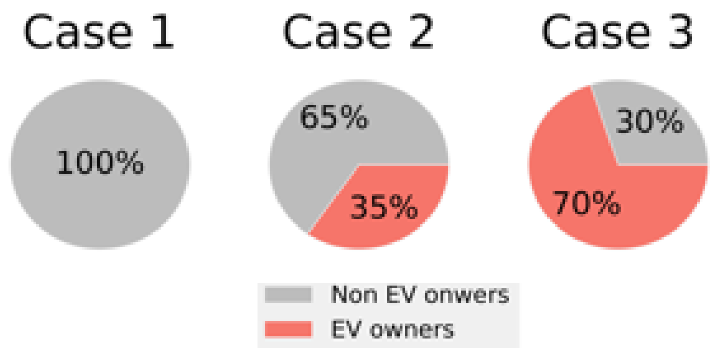


Figure 34: Illustration of the three EV-cases used in the case study

PV cases	Case 4	Case 5
Non EV owners for both cases:	30 %	
EV owners for both cases:	70 %	
Total installed PV capacity	20 kW	52 kW

Table 12: PV cases

6.3 PV model

The PV model was designed with solar irradiation values from the European Commission, Joint Research Centre and their software Photovoltaic Geographical Information System (PVGIS). Here, an average daily profile with hourly values can be found for every month, at any GPS coordinate in Europe. The inclination and orientation of the PV system are also taken in to account, creating hourly irradiation for a fixed plane. The irradiation values are average global irradiation for a fixed plane where the maximum irradiation occurred during May and was around $700W/m^2$ when the GPS coordinates for Järfälla was used (PVGIS, 2017). The parameters used for this PV model are stated in table 13.

PV parameters	
Inclination	35°
Orientation	0° (SOUTH)
Power factor (cos phi)	1

Table 13: The inclination and orientation values chosen for the collecting of irradiation measurement. The power factor used in the simulations is also displayed.

The PV model resulted in an average daily profile with hourly values for each month which was then used for each day of the given month. To clarify, the total maximum power delivered by the installed PV systems was 20 kW in the first case and 52 kW in the second when irradiation peaked. The power delivered by the PV systems then changes according to the hourly irradiation values that were taken for the GPS coordinates in Järfälla. The PV model did not include a battery for storage of surplus energy.

6.4 Analysis

For all the given scenarios in figure 34 and table 12 transformer loading and current were calculated. In *Chapter 5 - Future load behaviour and financial analysis* transformer utilisation rate was calculated using aggregated load from all customers. In this case study transformer loading was calculated using the actual current in the transformer divided by the rated current. The same logic as in power rating applies, meaning that current over the rated current is acceptable, but only for a few hours. Rated current was calculated using equation 15

$$I_{rated} = \frac{S_{rated}}{\sqrt{3} * U_{0.4}} = \frac{300}{\sqrt{3} * 400} = 433A \tag{15}$$

Voltages were calculated for every customer as well as for every electric cabinet. The buses that were modelled as customers were assigned the hourly values from the *Chapter 5 - Future load behaviour and financial analysis* as load with a fixed power factor of 0.98. The EV charging model was assigned randomly between the customers according to the distribution in figure 34. Voltage was then calculated (in per unit) for every bus. The bus with the **highest** voltage deviation from nominal(corresponding to no load) was used for the scenarios.

For the cables, loading was calculated at each time step. Loading in this case is actual current divided by the maximum current that could be transported. As for voltage, cable with the **highest** loading was compared for the different scenarios in figure 34 and table 12. With loading in each line combined with the information about the fuses used in the households from SAP it was also possible to calculate if the highest measured current were higher than household's fuse.

6.5 Result

6.5.1 Transformer loading

The charging of EVs had an obvious impact on the total load in the grid and therefore the loading of the transformer. As seen in figure 35 the scenarios with EV charging raised the consumption, especially during peak hours. *Chapter 5 - Future load behaviour and financial analysis* showed that the substation could be in need of an upgrade because of the high utilisation factor. Figure 36 displays the 25 highest values in the transformer loading duration curve. It shows that even though the transformer utilisation factor is high, total hours over 100% loading were less then eight for the case with 70% EVs. As for the PV systems, figure 37 displays that even for the second PV scenario, the PV systems had no impact on the power peaks. During summer the PV systems lowered the loading of the transformer to almost 0% during certain hours.

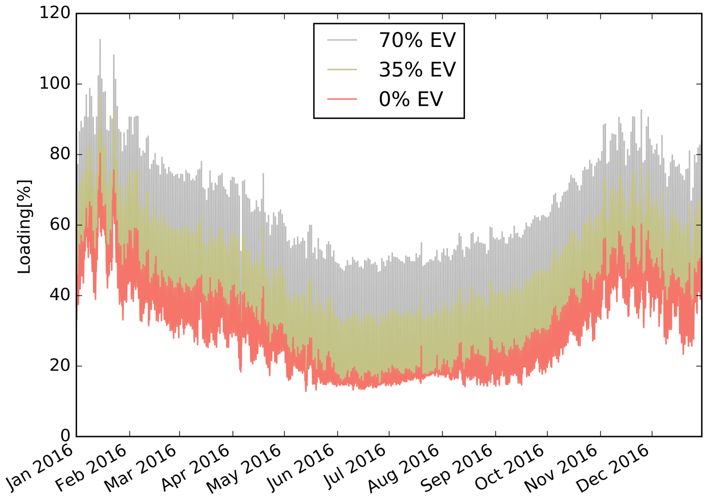


Figure 35: Stack plot with calculated loading profile $[I/I_{rated}]$ for the transformer used in the case study as base. The red line illustrates the case with no EVs. Both cases with a penetration of EVs are seen stacked on today's case with peaks according to the EV-model

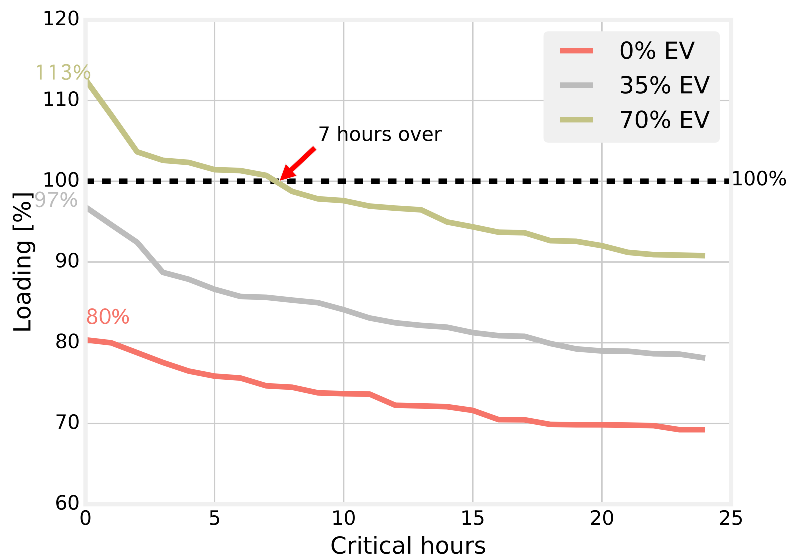


Figure 36: Duration curve for the transformer with the 25 most critical hours in terms of transformer loading. The left numbers are the highest calculated transformer loadings for the cases (with the PV cases behind the case with 70% EVs).

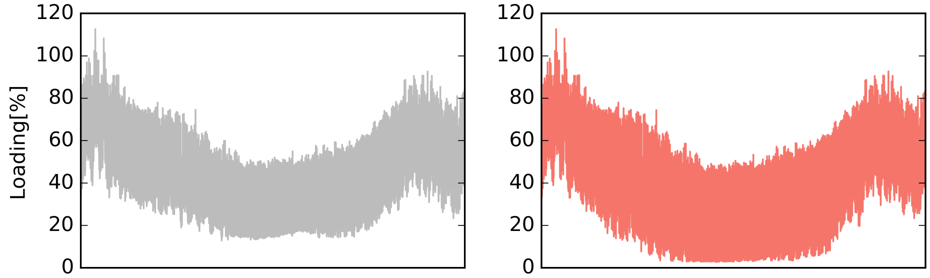


Figure 37: To the left is transformer loading for case 3 with the 70% penetration of EVs. To the right is transformer loading for the second PV case with 70% EVs and a total installed PV capacity of 52 kW.

6.5.2 Voltage deviation

As seen in figure 38 voltage deviations were in the range 0-4% from 0.4kV. E.ON guidelines for voltage deviation in the distribution grid state that voltage should not exceed +6% or -10%. Figure 38 and 39 only display the bus with the highest voltage deviation, which means that every other bus was below these limits. The bus with the highest voltage deviation was a customer located on the very edge of the branch with 7 customers connected to it.

The PV systems did not have any affect on the voltage during the most critical peak hours (which can be seen in figure 39 where case 4 and 5 is behind case 3). The PV systems did have an impact on the summer hours when production for the bus was higher then the load. For some hours production was higher than demand which lead to voltages above 1 per unit which are seen in figure 38. To summarise, most of the voltages below the nominal voltage were due to the EVs (without the help from PV) while voltages above were due to PVs.

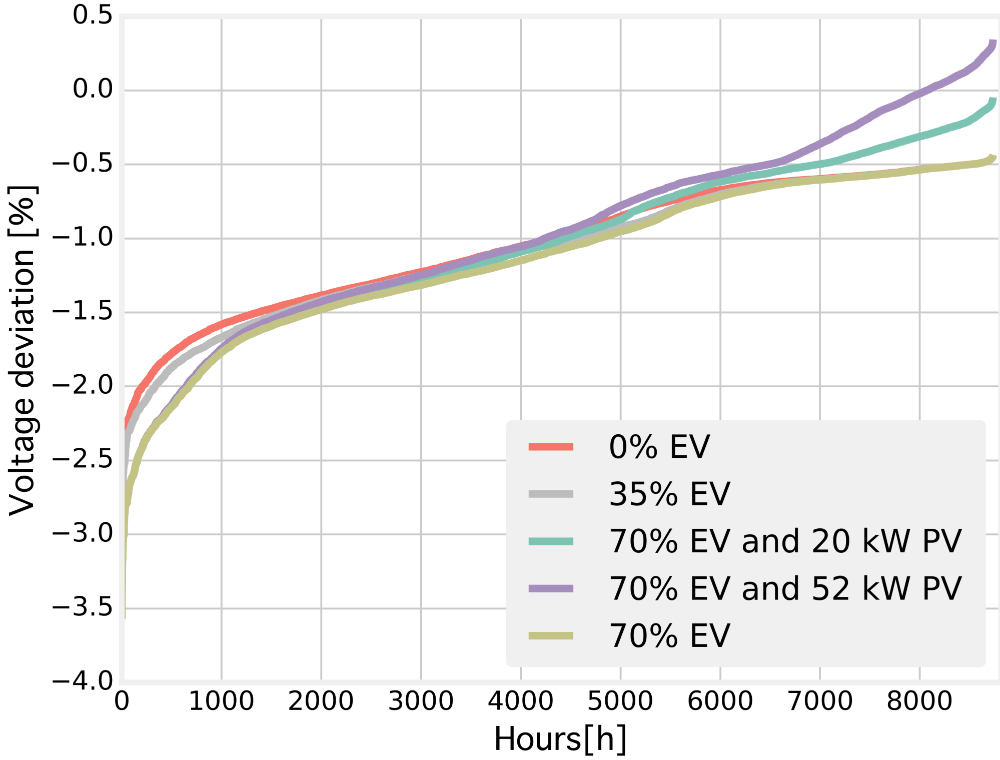


Figure 38: Duration curve for voltage deviation below the nominal voltage for the bus with the highest deviation. Case 5 with PV production gave a deviation above the nominal voltage for certain hours.

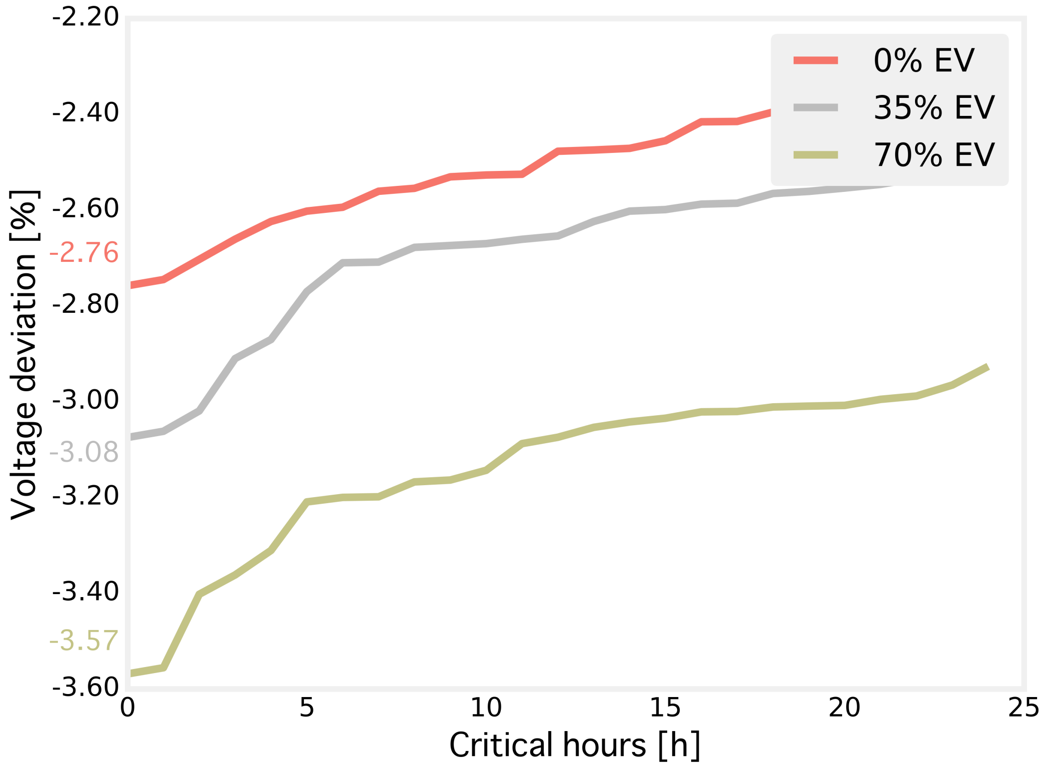


Figure 39: Duration curve for voltage deviation for the bus with the highest deviation. The picture is a close up of the upper left corner of the graph in figure 38.

6.5.3 Cable loadings

Figure 40 and 41 display that cable loadings where below 55% for all cases. In this network the cables connected to households had a maximum current in the range of 57-78 A and therefore a higher limit than the fuses. As for the voltage analysis it was clear that the PV systems did not have any impact on loading for the hours most critical to EV charging.

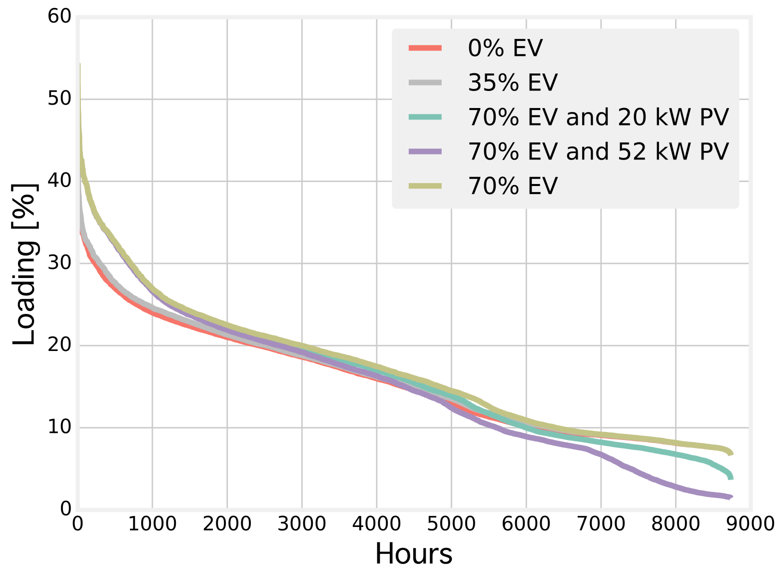


Figure 40: Duration curve for cable loading[I/I_{max}] for the cable with the highest loading.

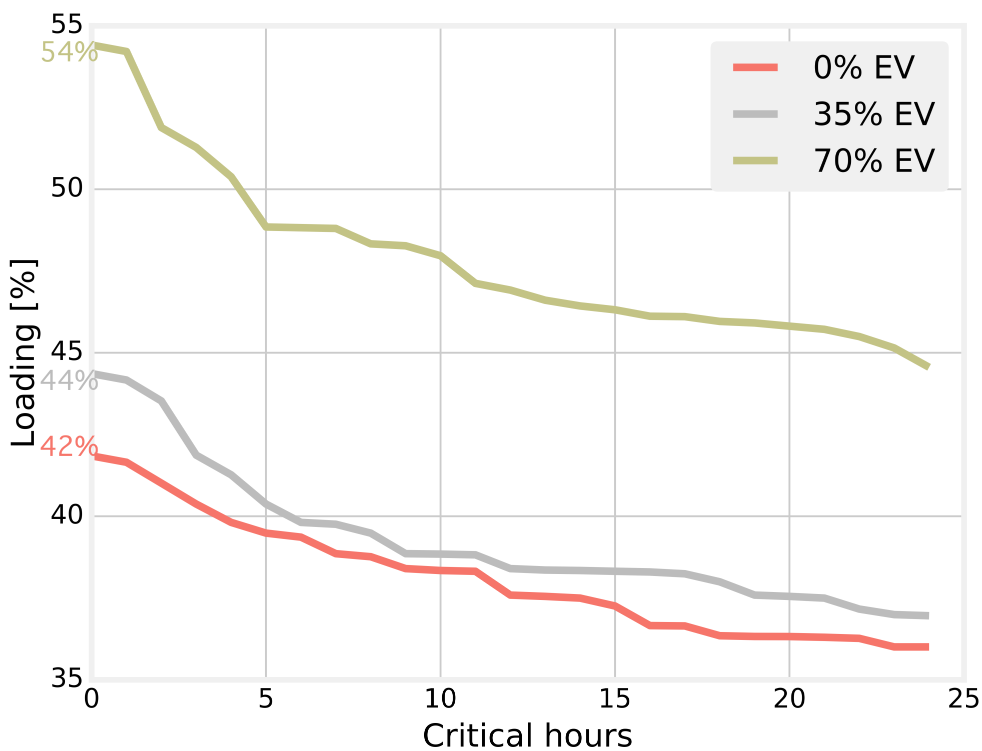


Figure 41: Duration curve for cable loading[I/I_{max}] for the cable with the highest loading. The picture is a close up of the left end of the graph in figure 40.

To further explain, the cable with the highest loading was an 95 mm^2 aluminium cable with a maximum allowed current of 230 A. The highest current that occurred was 124.2A. The maximum loading was then calculated as seen in equation 16.

$$Loading_{cable} = \frac{I_{cable}}{I_{cable,max}} = \frac{124.2A}{230A} = 54\% \tag{16}$$

With the cable loadings it was also possible to analyse the currents transported to the customers. The current transported in the cable to a customer's connection point was assumed to be the delivered current to the house. As a result it could be measured if the current was higher than the customer's fuse. The maximum current during the year was compared with the fuse. Table 14 shows the percentage of customers that had a maximum current above the fuse rating.

Scenario	Share of customers
0% EVs	0%
35% EVs	0%
70% Evs	8.57 %

Table 14: Percentage of customers that had a maximum current above the fuse rating

7 Discussion

In order to more accurately calculate the capacity in the distribution grid, hourly consumption is needed for all customers. One could have used quarterly values but this would have been even harder to obtain. Unfortunately E.ON does not have hourly measurements on more than 13,000 customers which complicated the task for us. In our best efforts to work around this predicament, we turned to mathematical statistics. Even if 13,000 customers is not enough on their own, it turned out they could be used to create a satisfying regression model.

The advantage with our model is that it describes 2016 quite accurately. One can, for instance, see in our yearly profiles that the peak loads occur in January. Observation of the mean temperature in January during 2016, shows that it is slightly colder than usual. This fact further strengthens our case that the grid is well-dimensioned for future penetration of EVs.

The biggest flaw in our approach is that the model is not predictive. This means that the model only represents the past year and cannot give any insight into the following year. For example, it would be interesting to see the resulting peaks when the temperature drops to $-20°C$. If we had a predictive model the load situation in these extreme cases could have been simulated. As also mentioned, the analysis skipped a portion of substations due to them having less than 5 connected customers. This was also due to an inferior model, which if enhanced could include all substations.

Another challenge in this analysis was to predict a realistic charging pattern. Advanced methods like Monte-Carlo simulations or other binomial probability distributions require a lot of empirical research to be used. Even then they are not certain to reflect the behaviour of real consumers. We chose to take a more simple approach when we modelled charging patterns. Using the normal probability distribution (with limits) intuitively seems fitting, since it is not far fetched to believe that people charge when coming home from work. Due to the complexity of the phenomenon, we chose a model that will likely be a worst case version of reality. To clarify, it is unlikely that the charging pattern will be so concentrated around 18.00 as the normal distribution states.

Anticipating the future penetration of EVs in Sweden was also difficult. However, a lot of reports have been written on this topic and therefore we simply chose to rely on external sources. We cannot evaluate the accuracy in the estimations other than that we believe it is reasonable. Even so, government subsidies, as stated in *Chapter 3 - EV and PV overview*, can have a accelerating impact on the development of EVs. Therefore, we chose to have, aside from our base case, a scenario with a rather large penetration of EVs.

Yet another uncertainty is with what power the EVs will be charged with. We believe that is a common misconception that EVs will be charged in the same way as you fill up your gasoline car. Restoring the energy in your car will more likely follow the same pattern as when you plug in your smartphone. Whenever the opportunity to charge arises, you are likely to do it rather than waiting until the battery is depleted. For instance, when parking at shopping malls or at a work place, we believe that semi-fast to fast charging will occur. Therefore, when arriving home, the battery state of charge will not be low and need only to be topped up. We then arrive at the conclusion that home charging most likely doesn't need to charge the entire battery. Coupled with the fact that average daily driving distance is nowhere long enough to consume all energy in the battery, we strongly feel that 3.7 kW charging is sufficient. Finally, this charging power can in many cases be used with the already installed fuse. Though in some cases, as has been presented, the customer has to upgrade its fuse. If for example semi-fast charging was to be used, almost all customers would have to consider upgrading their fuses, which does not feel realistic.

Another assumption that was made was the distribution of EVs between urban and suburban regions. The phenomenon of so-called reach anxiety seems to be a big obstacle when buying an EV. Naturally, the distances travelled when living in suburban regions and in the country-side are longer than in the cities. We therefore believe that the people in these areas are less likely to buy an EV than the people in the cities. In the vast majority of the cases, the numbers clearly state that the current batteries cover the average daily need by a large margin. However, a conservative mindset will probably ignore these facts. Another aspect is of course that the environmental benefits with EVs play a much larger role in the cities. Pollution and air quality are problems that future cities will have to address. Excluding fossil driven vehicles from the city centres will be an important step towards cleaner cities. The distribution we have chosen is estimated by us alone, and should therefore be revised at a later point in the future. However, we wanted to make a clear distinction between the two in order to enforce our arguments.

Even though there are both upsides and downsides with our model, the results are clear. The distribution grid is well prepared, should sudden increases of capacity need arise. The analysis clearly relays that the transformers have margin to overloading. Additionally, the results from the case study further enforces the belief of a well-dimensioned distribution grid. Even though the analysis is only for one of the 44'000 substations it could indicate if other factors than transformer utilisation factor could be at risk. Preferable this analysis would be done on all substations but due to the amount of work it would require it was suggested to look at one of those who seemed to have a high transformer utilisation factor. Even so, cable loadings and voltage are all well within E.ON guidelines. The only obstacle, as stated before, seems to be the fuses used in households. However, upgrades of fuses would only generate extra revenue for E.ON and should not be seen as a problem, diametrically, it should be welcomed.

It should be noted, that although the case study does not showcase the full potential of PV systems, it can still be very viable when paired with a battery. It is not investigated in this thesis, but the combination could be useful in order to lower peaks. Though, during winter irradiation in Sweden is very low whilst the network loading is at its highest.

While the result displays a strong financial case, it could actually be even more profitable than what is presented. The listed expenses are classified as non-affectable. This means that E.ON by law is allowed to increase their prices to cover for these costs, effectively removing the costs. However, E.ON's pricing today is not pushing its legal limit. On the contrary, it's actually quite far from it. As a consequence, increased non-affectable costs are not guaranteed to be covered despite law permitting.

Finally, the authors would like to convey some reflection on the software used for the case study, DPG.sim Academic. The program is intuitive and easy to understand. For inexperienced power system analysts, it is still possible to get started whereas other softwares like PSS/E requires a proper introduction and education. DPG.sim introduces a wide array of smart grid features that traditional programs lack. The distributors of the software provide great support. Though, like with all new softwares, there is not a community yet. This makes it hard to find quick answers to problems others would have encountered.

8 Conclusion and future work

The study evaluated the grid as it is today. It is clear that E.ON's distribution grid is well dimensioned today with a large margin to overloading in the majority of the substations.

A future EV penetration of 20% and 40% respectively with 3.7 kW charging for single family homes were used in this study. Adding in EVs will of course stress the grid, but only a fraction of the substations' ratings are overrun and need not necessarily be upgraded. The study made in Järfälla indicates that cable currents and voltage deviation are well within E.ON guidelines, even when charging occurs.

There are occurrences where substations have to be upgraded, and some investments in the distribution grid has to be made. However, they are almost negligible in the context and the revenue is far greater than the costs.

Our case study shows that PV systems will not aid in reducing power peaks due to EV charging as they produce power only during daytime. Though, coupled with a battery system, they could very well reduce household peaks during the evening.

With the current energy-based tariff everything points to that E.ON will profit from a large scale introduction of EVs. It is not evaluated though how it stands against a capacity based tariff. Switching to a capacity based tariff due to overloading caused by charging should not be an argument though, as has been clearly refuted in this study.

The authors would like to suggest some future work to make the analysis more complete. The single most important thing if E.ON would like to raise the quality of analyses like this is to store more data of hourly readings from customers. Also, an evaluation of the subtransmission grid should be made thoroughly. There might be capacity bottlenecks in that grid which are not taken into consideration here. Furthermore, a better mathematical model for predicting consumption curves should be developed. There should also be more case studies on grids to evaluate cable currents and voltage deviation and how they are changed during charging peaks. Finally, we suggest that revenue from a capacity based tariff is calculated to be compared with the energy based revenue.

9 Appendix

9.1 A

Zone	Type	Fuse	Monthly fee	SEK/kWh
MID-NORTH	House	16 A up to 8000kWh/år	198,75	0,3675
		16 A above 8000kWh/år	342,5	0,152
		20	505	0,152
		25	645	0,152
		35	942,5	0,152
		50	1423,75	0,152
		63	1885	0,152
NORTH	House	16 A up to 8000kWh/år	138,75	0,6405
		16 A above 8000kWh/år	452,5	0,17
		20	581,25	0,17
		25	737,5	0,17
		35	1052,5	0,17
		50	1537,5	0,17
		63	1966,25	0,17
MID-SOUTH	House	16 A up to 8000kWh/år	98,75	0,2855
		16 A above 8000kWh/år	212,5	0,115
		20	306,25	0,115
		25	417,5	0,115
		35	656,25	0,115
		50	1042,5	0,115
		63	1393,75	0,115
SOUTH	House	16 A up to 8000kWh/år	136,25	0,56
		16 A above 8000kWh/år	377,5	0,198
		20	500	0,198
		25	647,5	0,198
		35	950	0,198
		50	1422	0,198
		63	1850	0,198

Figure 42: E.ON prices in the zones used for the analysis

Revenue from charging energy (20% case)

The charging model was applied to the customers so that 20% of the cars were electric, and therefore had to be charged. For example, assume that a household has 1 EV. Charging with 3.7 kW during 3 hours then yields $3.7kW * 3h = 11.1kWh$. That is, the household has increased its consumption by 11.1 kWh per day. This gives $11.1kWh * 365d = 4051.5kWh$ additional consumed energy for one year.

Assume that this was a customer of type *House*, lived in zone *MID-NORTH* and had a fuse of 20A. This means that the cost of one kWh is 0.152 SEK. E.ON would therefore make an additional revenue of $0.152SEK/kWh * 4051.5kWh = 615.8SEK$. Since charging consumption, geographical zone and customer type are known, this can be done for all customers that was assumed to own an EV. This results in 63 MSEK, as is seen in the results.

Revenue from fuse upgrades

As it is hard to show the calculations made for each customer that needed an upgrade, an example will be given. Assume a customer of type *House* that has a fuse of 16 A, lives in the zone *SOUTH*, has a yearly consumption less than 8000 kWh/year and owns 1 EV. This customer has a consumption of 3 kWh/h during the evening. The maximum peak is therefore 3 kW. Further assume that the load is balanced, i.e. 1 kW per phase. When charging the EV, adding 3.7 kW to one phase will then result in a single phase being loaded with 4.7 kW. With the phase voltage 230 V, the new max current can be calculated as follows: $I_{phase,max} = \frac{4700W}{230V} = 20.4A$. This fulfils the condition $I_{max} = 20.4A > 1.1 * I_{fuse} = 17.6A$. The customer will therefore have to upgrade its fuse to 20A. This will work since $I_{max} = 20.4A$ is not greater than $1.1*20A = 22A$. Upgrading from 16A to 20A will cost $Price_{new} - Price_{old} = (500 - 136.25)SEK/month = 363.75SEK/month$ (see price list). Yearly total cost for the customer will then be $363.75SEK/month * 12months = 4365SEK$. This figure is the revenue that E.ON gets from the fuse upgrade on a yearly basis.

The consumption per hour (kWh/h) and installed fuse are known for all customers, and these calculations can therefore be made for each one. Doing so results in a total revenue of 250 MSEK and 512 MSEK for 20% and 40% EVs respectively.

Subscription fee to sub-transmission grid

Assume there is a substation with a yearly maximum peak of 500 kW. If EVs are added, the maximum peak increases to, for example, 600 kW. These are example figures, however they are known for all substations. In this example, E.ON has to pay the owner of the sub-transmission grid for the extra 100 kW. This would cost $100kW * 375SEK/kW = 37500SEK$ with the weighted price of 375 SEK/kW(internal price list). This is done for all substations, and if added together one arrives at a total increase of 269 MW for 20% EVs and 545 MW for 40% EVs. Finally, multiplying the increase with the cost gives $269 * 10^3 kW * 375SEK/kW = 101MSEK$ for 20% EVs and 205 MSEK for 40% EVs.

9.2 B

PROVNINGSPROTOKOLL

ABB

Typ: CTS-315/11PNSm DTSP-L3S137

Tillverkningsår **2012** **Serienr.** **1LPL498542**

Hsp					Lsp		
Märkeffekt [kV·A]	Spänning [V]	Reglering [%]	Ström [A]	Kopplingsgrupp	Märkeffekt [kV·A]	Spänning [V]	Ström [A]
315	11000	±2x2.5	16.53	Dyn11	315	420	433.0

Driftsförhållande	C	Kylning	ONAN	Totalvikt	1260 kg
Fasantal	3	Omgivningstemperatur	40 °C	Oljevikt	211 kg
Märkfrekvens	50 Hz	Isolationsklass	A	Order	1059142

Spänningen mätt med kompenseringsmetod: (Osäkerheten av mätvärderna är ±0.2%)

Hsp-läge:	1	2	3	4	5
Hsp [V]	11550	11275	11000	10725	10450
Lsp [V]	420	420	420	420	420
Avvik [%] A	0.05	0.05	0.05	0.05	0.05
Avvik [%] B	0.05	0.05	0.05	0.05	0.05
Avvik [%] C	0.05	0.05	0.05	0.05	0.05

Spänningsprov — Isolationsnivå: LI75AC28/AC8

Spänningsprov, 50 Hz, 1 min — Hsp 28 kV — Lsp 8 kV

Induserat prov Lsp, 250 Hz — 840 V — 24 s

Osäkerheten av mätvärderna är ±2%

Lindningsresistanser i Ω: Märkläge: 3 — Temperatur 24.9 °C

Hsp [V]	11000	Lsp [V]	420
A-B	3.35	a-b	0.00396
A-C	3.37	b-c	0.00395
B-C	3.38	c-a	0.00400

Osäkerheten av mätvärderna är ±0.3%

Kortslutningsprov (Osäkerheten av mätvärderna är ±2%) — Temperatur 24.9 °C

	Uppmätt			Belastn. förluster vid 75°C				Impedans vid 75°C			
Hsp/Lsp [V]	Spänning [V]	Ström [A]	Förluster [W]	Uppmätt [W]	Garant. [W]	Avvik [%]	Tolerans [%]	Uppmätt [%]	Garant. [%]	Avvik [%]	Tolerans [%]
-	-	-	-	-	-	-	-	-	-	-	-
11000/420	457.5	16.65	2748	**3133**	3200	-	0	**4.11**	4	2.81	±10

Uppmätt			Tomgångsförluster, 50 Hz				Tomgångsström, 50 Hz			
Spänning [V]	Ström [A]	Förluster [W]	Uppmätt [W]	Garant. [W]	Avvik [%]	Tolerans [%]	Uppmätt [%]	Garant. [%]	Avvik [%]	Tolerans [%]
420	0.48	309	**309**	340	-	0	**0.11**	0.24	-	+30

Osäkerheten av mätvärderna är ±2%

Oljetyp NYNAS-NYTRO 10XN — Transformatorn innehåller ej PCB — Oljenorm IEC 60296

INTYG

ABB, som tillämpar ett integrerat kvalitets- och miljöledningssystem i enlighet med ISO 9001 och ISO 14001, intygar härmed att den utrustning med vilken tester har utförts överensstämmmer med den internationella standarden EN(IEC) 60076-1 Datum: 06.10.2012

KIEROWNIK
Działu Kontroli Jakości
mgr inż. Paweł Pydyszewski

Namn och signatur (szwedzki)

1LPL100046-GW EON SE

Figure 43: Technical data on a 315 kVA transformer

9.3 C

Cost center	Amount
Upgrade station SS2	71 737
Upgrade transformer SS2	55 350
Upgrade station N3	260 000
Upgrade transformer N3	70 501
Upgrade station N8	311 077
Upgrade transformer N8	134 751
Additional city investment	700 000

Table 15: Costs used when calculating investment costs (Energimarknadsinspektionen, 2014). Figures are in SEK.

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