Impact of electric vehicle charging on the distribution grid in Uppsala 2030

EMIL GUSTAFSSON
FREDRIK NORDSTRÖM

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Emil Gustafsson, Fredrik Nordström

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Industrial Engineering and Management
ITM
Royal Institute of Technology
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Abstract

Planning of distribution grids is based on statistically estimating the maximum load that will occur given a certain range of criteria (location, household types, district / electric heating etc.) Charging of electric vehicles is not one of these criteria. However, given the expected ‘boom’ in sales of Chargeable Electric Vehicles (CEVs), and the lengthy planning process of distribution grids (¿10 years) the knowledge gap is becoming a more pressing issue.

This research has been conducted to investigate if Vattenfall, a Swedish electric utility company with distribution assets in both Sweden and Germany, needs to take action to react to the expected increase in CEVs in the near term. The study has been conducted with Uppsala Municipality as a showcase and 2030 as the time frame.

The findings of this study show that Vattenfall should incorporate CEV usage into distribution planning to avoid overload of power stations in Uppsala by 2030. The findings shows that 1) we can expect a ‘boom’ in sales of CEVs in the near future and that 73% of cars in traffic in Uppsala may be CEVs by 2030 and 2) that CEV charging is expected to have a significant impact on the distribution grid, with certain power stations in Uppsala seeing a peak load increase of up to 30%. The recommended actions are the following:

- Monitor specific areas with a high concentration of cars and low energy consumption per household that already have substations with capacity below the recommended dimensions
• Monitor CEV sales to reevaluate current projections on CEV development in Uppsala

• Monitor trends of car ownership and evaluate whether this will affect CEV charging behaviour

• Reconstruct Velander constants, used for grid planning, to take the CEV load into consideration

• Investigate smart charging solutions, to shift the CEV load peak to a different time of the day

**Key Words:** Chargeable Electric Vehicles, Load Profiles, Distribution grid, Driving Patterns
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Sammanfattning

Dimensionering av distributionsnät baseras på att statistiskt uppskatta den maximala lasten som kommer att inträffa på nätet, givet olika faktorer (geografiskt läge, hushållstyp, fjärrvärme / elvärme etc.). Laddning av elbilar är inte en av de faktorer som man tar hänsyn till. Givet en väntat kraftig ökning av laddningsbara bilar, samt den långa planeringshorisonten för distributionsnät (¿10 år), blir dock frågan hur elbilar kommer att påverka elnätet väldigt aktuell.


Resultaten från studien visar att Vattenfall bör ta hänsyn till laddning av elbilar vid dimensionering av distributionsnät för att undvika överbelastning på nätstationer i Uppsala år 2030. Resultaten visar dels att 1) man kan förvänta sig en kraftig ökning av försäljning av laddningsbara fordon inom en snar framtid och uppmot 73 % av alla bilar i trafik i Uppsala kommer att vara laddningsbara år 2030 samt att 2) laddningsbara fordon kommer att ha en signifikant påverkan på distributionsnätet med ökningar på upp till 30 % av maxlasten för vissa nätstationer. Följande åtgärder rekommenderas således:

- Övervaka specifika områden med hög biltätthet och låg energianvändning per hushåll som är anslutna till nätstationer som är underdimensionerade
• Följ utvecklingen av försäljning av laddbara fordon för att omvärdera genomförda projektioner över laddningsbara bilar i Uppsala.

• Övervaka trenderna inom bilägande och utvärdera hur detta påverkar laddningsbetande.

• Gör om Velandkonstanter så att de tar hänsyn till lasten från laddbara fordon vid planering av elnät.

• Utvärdera smarta laddningslösningar för att flytta last från elbilsladdning till en annan tidpunkt på dygnet.

Nyckelord: Elbilar, Lastprofiler, Distributionsnät, Körmönster
Declaration

'We declare that all material in this thesis is entirely our own work and has not been previously submitted to this or any other institution. All material in this thesis that is not our own work has been acknowledged and we have stored all material used in this research, including research data, preliminary analysis, notes, interviews, and drafts, and can produce them on request.'

Emil Gustafsson
Signature
May 29th, 2017
Date

Fredrik Nordström
Signature
May 29th, 2017
Date
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Abbreviations

BRD 1 Bilrörelsedata 1.
CEVs Chargeable Electric Vehicles. See Glossary: CEVs.
CTR Centre for Traffic Research.
ECS External Charging Strategies.
EVC Electric Vehicle Charging.
ICEs Internal Combustion Engines. See Glossary: ICEs.
ICS Individual Charging Strategies.
IVA Kungl. Ingenjörsvetenskapsakademien.
LSP Lindholmen Science Park.
MRQ Main Research Question.
SCB Statistiska Centralbyrå.
SOC State of Charge.
SVK Svenska Kraftnät.
TSS Test Site Sweden.
UCC Uncontrolled Charging.

Glossary

CEVs All cars that can charge and run on electricity. Two sub-categories to CEV are BEV (Battery Electric Vehicle) and PHEV (Plug-in Hybrid Electric Vehicle). EHV (Electric Hybrid Vehicle) is not considered a sub-category in this definition because it can not be re-charged with electricity through a plug.

Grid Load The electrical consumption on the electrical grid.

ICEs All cars that have an engine that work by burning fossil fuels such as petroleum and diesel.

Passenger Cars A car that is intended for people and a maximum of eight seats in addition to the driver’s seat.
**Power Train** The mechanism that transmits the drive from the engine of a vehicle to its axle.

**Velander Constants** Constants that are used to statistically help dimension distribution grids. They are based on electricity consumption habits to determine the annual peak load.
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1 Introduction

This section introduces the background of the thesis and presents the problem formulation. The purpose and aim as well as definition of research questions, delimitations and scientific contribution of the thesis is included in this section. Finally, the contribution to science that this research brings and a disposition of the report is accounted for.

1.1 Background

'A shift is under way that will lead to widespread adoption of electric vehicles in the next decade'

(Randall 2016)

The energy industry is facing a vast transformation. Energy production and storage are becoming increasingly decentralised and renewable energy production is becoming competitive with conventional generation. Industrial processes are shifting towards using electricity as the supply of energy and we are phasing out fossil fuels such as oil.

As a part of this transformation there has been a surge in demand for Chargeable Electric Vehicles (CEVs). Large investments and significant political incentives are driving the production costs down, leading to an eventual tipping point for sales of CEVs. This will cause a shift in energy distribution, putting a larger strain on the distribution grid and lead to a decreased demand in energy sources such as gas and diesel (Randall 2016).

To put this in perspective, Sweden’s total secondary energy consumption amounted to 375 TWh in 2015, of which 85 TWh came from the transport sector (accounting for cars, trucks and trains but not aviation). According to the Swedish Energy Agency, roughly half of the 85 TWh per year is consumed within the combustion engine of a car. Thus, roughly 11% of Sweden’s energy consumption is on the verge of taking a new route (The Swedish Energy Agency 2015).

As of December 31st 2016 there were roughly 27,000 vehicles in Sweden that could be charged with electricity. 29%, or 7,532, of these vehicles run on electricity
only (BEVs as opposed to PHEVs), compared with the total number of passenger cars in Sweden which was approximately 4.8 million in 2016 (Power Circle 2016c).

During 2016 there was an increase of 65% in sold CEVs and, if historical sales are extrapolated, it is projected that by the end of 2020, the number of chargeable vehicles in Sweden will reach 152,000 (Power Circle 2016c). If the rate of newly bought CEVs will continue as it has, 58,000 new CEVs will be sold in 2020 (Power Circle 2016a). To put this in perspective, 388,000 new cars in total were sold in Sweden in 2016 (Transport Analysis 2017a).

On average, a passenger car in Sweden travels 34 km per day, varying depending on where in Sweden you live (Myhr 2016b). Given these 34 km, an electric car like a Nissan Leaf would have to charge approximately 6 kWh per day (Nissan 2016). As a comparison, a typical refrigerator has a power usage of 50 W which, during the course of a day, amounts to 1.2 kWh or a fifth of the consumption of a CEV (Electolux 2016).

Electricity producers are constantly working to match the supply and demand in the system and this process has been relatively unchanged and consistent. People sleep at night, wake up in the morning, eat breakfast, go to work, return from work, make dinner and go to bed - people’s daily routines are the primary driver for the electricity demand on a local level and it is from this behaviour, together with criteria such as geographic location and type of household, that the distribution grid is dimensioned today. The planning process for distribution grids is long (≥10 years) and needs to account for changes in demand expected in the future. While there is uncertainty in terms of what will happen when, the electrification of the transport sector is inevitably going to affect grid planning activities.

1.2 Problem Formulation

A major and dramatic increase in CEVs will not happen overnight, however, it is likely that all actors in the Swedish electric grid will see effects in the upcoming 5 - 10 years (see Section 3.1). Given that the total energy consumed by passenger cars is comparable to the total amount of energy consumed in Sweden, it is relevant
to evaluate increased variations of the grid load. These variations may be very compatible with the current load profiles, resulting in a flatter demand profile, or they may, conversely and more likely, cause extreme load peaks and put an unsustainable strain on the grid. Since charging of electric vehicles is not one of the criteria that is taken into consideration when dimensioning distribution grids, and the planning process is long, the knowledge gap of CEVs impact on the grid is becoming a more pressing issue.

Specifically, there is little knowledge of how this will affect specific urban areas, such as Uppsala. The problem is not primarily regarding the average demand and the average capacity, but rather what will happen in certain extreme scenarios. For example, during the end of the day when people come home from work, on holidays taken by car, etc. The current unpredictability and uncertainty may cause distress in the electric grid once sales of CEVs start to pick up. This distress may cause larger load peaks in the grid, requiring a need to expand the distribution and transmission capacity, which is very costly. The increased demand may however end up causing a better balance in the demand, for example, by CEVs charging during low peak demand hours. Whether the increased loads from the CEVs mismatch with the current load profiles or not, it can be assumed that actors such as Vattenfall will benefit from knowing which.

1.3 Purpose and Aim

The purpose of this thesis is to map out and investigate the effects of CEVs on the distribution grid in Uppsala. The aim is to evaluate if Vattenfall need to take action to react to an increase in CEVs and, if so, determine which measures Vattenfall should take.

1.4 Research Questions

The research questions have been structured through a Main Research Question (MRQ) with two sub-questions (SQ). These are as follows:

MRQ Which measures should Vattenfall take in order to sustainably react to the
expected increase in CEVs in Uppsala by 2030?

SQ 1 How many CEVs and of what kind will there be in Uppsala and in relevant nearby areas in 2030?

SQ 2 How will CEVs impact the distribution grid in Uppsala in 2030?

1.5 Delimitations

This thesis will geographically be limited to investigating the MRQ in Uppsala Municipality due to its relevance and interest to Vattenfall as grid owner. The results will therefore be most relevant in Uppsala Municipality but will be valid as an indication to other municipalities.

When collecting and using different data there are limits to what is accessible. This makes it necessary to adjust the data in order to fit Uppsala and CEVs by making assumptions and generalizations. This is described further in Section 2.

As projections of CEVs primarily regard passenger cars, this study will focus only on the driving patterns of those. Passenger cars leased through employers/companies, taxis and other commercial passenger cars will all be included as they are not excluded in current reporting systems and databases (Myhr 2016a).

When looking at Electric Vehicle Charging (EVC), the limitation that the charging is to be 100% done at home is made. This for two reasons, firstly, because evidence points to home charging being the absolutely most common way to charge your electric vehicle, and secondly, to ensure that the ‘worst case’ scenario from a distribution grid perspective is covered in the study. More on this in Section 8.

Finally, since this thesis is conducted together with Vattenfall, the suggested measures to be taken will be tailored to Vattenfall and Uppsala Municipality, but will be applicable to other energy companies and municipalities as well.

1.6 Contribution to Science

Previous studies conducted in the area of CEVs’ impact on the grid load mainly focus on the present situation as opposed to taking a longer projection into account. Existing literature examines national grid effects from different perspectives and
what implications CEVs will have on a country as whole. This thesis will have a more narrow perspective and assess the effects on a specific municipally (Uppsala), at specific times and the implications different future CEV scenarios will have on the local grid in terms of supply and infrastructure.

Also, this study is unique in the sense that it uses detailed transport data to translate peoples’ driving patterns into load profiles. This methodology has not been found in other research.

1.7 Disposition

This report presents the conducted research and it is structured in the following way.

**Introduction** This chapter starts by giving the reader of this report a background and problem formulation of the chosen area of research. The chapter then includes the purpose and aim and the specific research questions followed by the delimitations of the study and the research’s contribution to science. The chapter ends with describing the disposition of the report.

**Method** This chapter describes how the research have been conducted in order to achieve the purpose and aim of the study and to answer the research questions. The chapter starts with describing the research approach and the research process, followed by explaining how the collection of data and the analysis of the model outcome will be done. The chapter then ends with describing how the research will ensure validity and reliability.

**Literature Review** This chapter aims to provide the needed knowledge and theory in different areas, in order to conduct the research in a good way. The chapter includes research on the development of chargeable electric vehicles, modelling of driving patterns and how the electric grid works.

Proceeding these generic chapters, the results of this study will be presented accordingly.
CEV Projections 2030  This chapter presents the findings regarding the CEV projections that have been compiled for this study

Analysis of Driving Patterns  This chapter presents the findings regarding the analysis of driving patterns to present a hypothesis on when and how much CEVs will need to charge.

CEVs’ Impact on the Uppsala Grid 2030  This chapter combines previously presented results with the current grid load to be able to isolate the impact due to CEVs. This chapter also includes a sensitivity analysis to illustrate how possible errors in the collected data might affect the findings.

Results  This chapter summarizes previously presented findings and answers the research questions asked in the beginning of the report.

Proceeding the results, the report ends with the following generic chapters.

Discussion  This chapter discusses the reliability of the empirical findings and the impact that the results have. It also discusses scenarios and externalities that might affect the results as well as discusses some of the assumptions that have been made.

Conclusion  This chapter concludes the research by answering the main research question. It also leaves suggestions regarding future research to be done in order to expand the field of knowledge.
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2 Method

This section presents the chosen methodology used in this thesis. The section includes a description of the research approach and the research process and presents the chosen data sources and modelling method. The section ends with a reflection on the quality of the research design.

2.1 Research approach

In order to fulfill the purpose and aim of this thesis there was, firstly, a need to model and simulate both CEV development, grid load patterns and travel patterns to determine how these, together, will impact the electric grid in Uppsala Municipality 2030. Secondly, there was a need to identify potential measures for Vattenfall to take given this insight.

To be able to achieve the first part we’ve had to identify the needed data in order to create the necessary model to simulate the situation in Uppsala in 2030. This was done both together with Vattenfall and other institutions (see Section 2.3). We then chose to compare the current situation (in terms of electricity usage today) with our analysis of how CEVs will affect the grid in 2030. This was done in terms looking at the change in needed power.

Furthermore, once the necessary data was in place and analyzed, we were able to propose recommendations on how Vattenfall should further monitor and be proactive to the expected increase in CEVs.

2.2 Research process

The driving factor behind this thesis idea has been our interest in the CEV area combined with Vattenfall’s interest to learn more about how they will be affected by the expected CEV development. Vattenfall wanted a better understanding of how CEVs will affect them as grid owners in the future and what actions they need to take to be proactive.

After discussions and a better understanding of both previous research (together with supervisors at KTH) and Vattenfall’s need of insight in the area, the MRQ
was established.

Once the MRQ was determined, the problem was broken down into its component parts. This was done by usage of a problem solving methodology by McKinsey & Company (2017). The used process of breaking down the problem can be seen in Figure 1.

Simultaneously while structuring the problem, a literature review was commenced to increase the knowledge in chosen areas. These areas were CEV Development, Modelling of Driving Patterns and The Electric Grid. The knowledge acquired from the literature review was then used in the investigation process as a frame of reference, as suggested by Collis & Hussey (2013).

When completing our research which includes conducting interviews, searching for the right data sources, building our model, and compiling and discussing results, a certain chain of process has been used. Figure 2 illustrates the research process that has been used throughout the making of this report.
2.3 Collection of data

As mentioned, an important part of our research consist of identifying and collecting the right type of data to enable us to answer our MRQ. Our study has focused on existing data since gathering own data is technically difficult and time consuming. This subsection presents how we found the right data with the sources we used and why.

2.3.1 Projecting CEV development

To be able to answer the question of how CEVs will affect the electric grid in the future, there was a need to estimate how many CEVs there will be, where these will be used and what technical specifications they will have.

To determine how many CEVs there will be and where, our primary source has been the Swedish Transport Analysis’ database (hereinafter Trafa). The database provided us with information regarding number of new cars sold (by fuel type), both in Sweden as a whole and on a regional level (municipalities). Trafa also provided information on the total number of cars that are in traffic in Sweden (by fuel type and region) and the development over the past years. (Transport Analysis 2017b)

Trafa is a state agency and is therefore seen as a credible source of information as their primary objective is to present objective and impartial facts.

Another source that was used for conducting CEV projections was the database ELIS (Elbilen i Sverige). ELIS is operated and maintained by Power Circle (interest group of the Swedish energy sector) and consist of statistics regarding CEV sales as well as projections for the future. ELIS is seen as a reliable source and a good
2.3.2 Modelling drive patterns

The next step was to gather data on how people in Sweden and Uppsala are using their cars, to be able to say how the usage of cars will affect the grid when replaced by CEVs. When acquiring this data, collaboration with Lindholmen Science Park (LSP) and Test Site Sweden (TSS) was crucial for our research. LSP is an international collaboration for research and innovation based in Gothenburg, Sweden. LSP have three focus areas which are Media, ICT and Transport, the later is where the TSS-program is situated. (Lindholmen Science Park 2017)

Within the TSS-program is the so called National Car Movement database that consists information on different car monitoring projects. The database is financed by The Swedish Energy Agency (Energimyndigheten) and the purpose of the database is to gather information on how CEVs and ICEs actually are being used (Test Site Sweden 2017). This database is open for non-profit organisations and research and it is from this database that we gathered data to determine driving patterns. Both LSP and TSS are seen as credible sources of information as they are publicly funded, non-profit and share the unmanipulated raw data.

Two other important sources in modelling driving patterns was Uppsala Municipality and Trafa. These sources provided statistics on where in Uppsala there are many cars (demographic statistics) and what the average driving distance in specifically Uppsala is. This information helped translate the data from the TSS database to be applicable for the drivers in Uppsala.

2.3.3 Understanding the grid

Lastly there was a need to acquire data about the local electric grid in Uppsala, to understand the components that make up the grid and what the implications to change these would be. We needed to understand how the grid is constructed and how the different system components interact with one another and understand how the grid load is today and how it might change.

The necessary information was retrieved by reaching out to people at Vattenfall
and other organisations to gain the specific and expert insights needed. According to Blomkvist & Hallin (2015), semi-structured interviews is a good method to collect qualitative data and thus this strategy was adopted in these meetings.

There was also a need to compare the load from CEVs to detailed household load. This was our chosen method when investigating the effects on the grid due to CEVs because the relative change from today’s household indicates how the current infrastructure may need to be upgrade.

We simulated the CEV load by combining the driving patterns data of when and how much the CEVs would need to charge with our research on technical specifications of CEVs and CEV chargers. The household load profiles were constructed using historical data provided by The Swedish Energy Agency. The data was provided as Excel sheets with information on different types of households, different sources of electricity usage and for different time periods. This made it possible for us to conduct our analysis in a good way.

The data from The Swedish Energy Agency is deemed as reliable, since it comes from a public agency and since acquiring the data was done under strict regulations and measurement rules.

2.4 Analysis of data and model outcome

When all the necessary data had been collected we had to compile the different data sources into one to be able to analyze the data and produce results. This subsection describes the methodology for doing this in the best way.

2.4.1 Software choice

We used Microsoft Excel as our primary software for compiling the data, creating our model and making our analysis. Excel was deemed to be the best tool as it is easy to handle large amounts of data in and since we have a good understanding of the software and its functions. Add-ins such as PowerPivot was used to handle the databases and VBA-Macros was used to extract final results.
2.4.2 Value-creating results

Ultimately, the purpose of this study was to find what actions Vattenfall should take in order to, in a sustainable way, react to the effects CEV charging could have on the electric grid in Uppsala by 2030. Thus, it was important to constantly have this in mind during the length of the study so that we did not drift from that purpose. In order to assure this, constant feedback and weekly sessions with supervisors at Vattenfall was held.

2.5 Validity and Reliability

To ensure that the report is conducted in a proper way we made sure to check the validity and reliability thoroughly throughout the entire length of the study. This is crucial to be able to guarantee that an external and objective party would be able to conduct the same research as we have and reach the same results (Collis & Hussey 2013). This was done by presenting all the results that were generated including notes from interviews and meetings to ensure complete transparency. By ensuring this the research becomes more reliable and useful to those reading this report.

According to Blomkvist & Hallin (2015), validity is to make sure that the conducted research is about the right thing and reliability is to ensure that the research is done in the right way. Since this study consists of both gathering of data and simulation of results, it is important to ensure validity and reliability of the input data to be able to ensure validity and reliability in the results themselves. To make sure that the collected data is both valid and reliable the data was analyzed by triangulating the data points using different independent sources (Trafa and ELIS as well as TSS, Uppsala Municipality and The Swedish Energy Agency). This is encouraged, according to Easterby-Smith et al. (2012).

Since we simulated scenarios to obtain the results the most important factor threatening the reliability and validity of the results is the quality of the data and the number of parameters included in the model. However, we ran the risk of the validity conflicting with the reliability since an increase in the number of
parameters could compromise the accuracy of the results. We aimed to calibrate this in collaboration with experts on the subject of modelling as well as experts in each sub-area of the study.

Normally, interviews can cause risks with the reliability of the results, however for this report, the interviews were primarily a source of objective information on how things are. Thus, no personal opinion was expected to effect the outcome.
3 Literature Review

This section presents the required background and relevant conducted research for this thesis. Firstly a general background is provided on the CEV market, different CEV models and the CEV charging infrastructure. Further, the chapter will look into how driving patterns are identified and quantified as well as make a deep dive into the electric grid and what current load profiles look like. Finally the chapter summarize previous research that is specifically relevant to this thesis.

3.1 Chargeable Electric Vehicles

This subsection brings to light the development within the CEV industry. This includes the sales trends, development from different car manufacturers and the charging infrastructure.

3.1.1 Market for Charging Electric Vehicles

The market for CEVs is nearing a tipping point. In 2015 the global CEV market surpassed 1 million CEVs globally on the streets. This is illustrated in Figure 3. China is today the biggest CEV market in terms of number of cars sold with roughly half of all new CEV (350,000) sold in 2016 (Alestig & Hjalmarson-Neideman 2017).

![Figure 3: CEV global growth (International Energy Agency 2016)](image-url)
Seven markets have reached over 1% in market share (share of new cars sold) where Norway (which has the highest market share for CEVs) and Netherlands have come especially far with 23% and 10% respectively (2015). This is illustrated in Figure 4.

![Figure 4: CEV market share by country (International Energy Agency 2016)](image)

Sweden is routinely named as one of the next countries that is expected to catch on in the transition to CEVs. During 2016 chargeable vehicles accounted for 3.2% of new car sales, up from 0.53% 2010 (Power Circle 2016b). As of 28th March 2017, the 2017 share is 4.6%. In Uppsala Municipality the development of CEV has been similar to that of the entire country. In Figure 5 - Figure 8, the development of both total number of cars (by fuel type) and number of CEVs in Sweden and Uppsala Municipality the last three years is presented.

Projections made by Vattenfall and Power Circle claim that 1 million CEVs will be on the Swedish roads by 2030 and approximately 25,000 of these in Uppsala county (Power Circle 2016b). At the same time, an investigation by the Swedish government (SOU 2013:84) from 2013 claimed that Sweden would reach just above 0% CEVs in 2030 and 10% in 2050, numbers that today are already surpassed (A-
A new study by Bloomberg New Energy Finance predicts that 35% of new cars sales worldwide will be chargeable by 2040 (Randall 2016).

In the middle of the 2000’s, cars driven by ethanol were strongly subsidised by the Swedish government (tax deductions on both the car and on the fuel). This resulted in massive growth in sales for a couple of years, which later stopped completely, mainly due to the subsidies being withdrawn in 2011 (Saxton 2016).
development of ethanol cars sales shows how strong incentives, like subsidies, have a powerful effect on peoples buying behaviour.

CEV sales have also been driven mainly by governmental subsidies. Both Norway and the Netherlands offer significant tax cuts as incentive for buying a CEV instead of a traditional petrol driven vehicles (Kihlström 2015). In Sweden the so called *supermiljöbilspremien* gives CEV buyers a discount of up to 40,000 SEK (Finansdepartementet 2016). The Swedish government recently extended the *supermiljöbilspremien* in waiting for the *Bonus-malus-system*, designed to penalize cars
with high emissions. The *Bonus-malus-system* is expected to be in working order by July 1st, 2018, and with that the *supermiljöbilspremien* will cease to exist. (Finansdepartementet 2016). There are other factors expected to fuel the growth such as decreased prices of CEVs, longer driving range and improved access to charging infrastructure.

When comparing the CEV development in Sweden and Norway, it looks like CEV development in Sweden is following a similar development, only three years later. This is seen in Figure 9 and Figure 10. The comparison between the two countries is relevant as the two countries are very similar from an economical, geographical and social perspective.

![Figure 9: CEV market share development in Sweden (Transport Analysis 2017a)](image)

### 3.1.2 Car model development of Electric Vehicles

Car model development of CEVs and increased sales is in a positive spiral, driving down prices and increasing the number of available car models. Increased demand is driving down the cost for the batteries used in the cars which is especially important because it accounts for roughly 75% of the total power train cost (Wolfram & Lutsey 2016). Since 2010, battery prices have dropped 65% and in 2016 alone they dropped 35% (Randall 2016). According to Randall (2016), price parity will be reached by 2022, at which point the life time cost for owning a CEV will be equivalent to
owning a regular car with an internal combustion engine. Randall (2016) makes the comparison to other technical transitions and states that ‘there comes a time when the old technology no longer makes sense’ and that it is at that point when the real transition begins. This transition is predicted to occur during the 2020s according to the report from Bloomberg New Energy Finance.

As a consequence of the rapid growing CEV market, almost all of the major car manufacturers have a clear CEV-strategy, both for today and for the years to come.

**Volvo** have stated that they aim to produce 1 million electric cars by 2025 (Volvo Car Group 2016).

**Volkswagen** stated back in 2015 that they would have a lineup of 20 electric vehicles by 2020 (Bloomberg 2015). The latest statement is that Volkswagen will have 30 models in 2035 and that they will spend $2 billion on charging stations (Muoio 2017).

**Ford** has announced that they are allocating $4.5 billion in CEV development and that they are planning to have 13 CEV models in their lineup by 2020 (Hwang 2016).

**Honda** claims that two-thirds of their line-up will be electrified by 2020 (Hwang 2016).
Daimler is spending $500 million on a new battery factory to support their CEV cars (Hwang 2016).

Tesla is building their 'Giga factory' for battery production in Nevada and are hoping to cut their battery costs with over 30% when finished in 2018. Tesla estimates that the factory will be able to produce an annual battery capacity of 35 GWh (Tesla Motors 2017).

Besides what is mentioned above, the Asian market (with China leading the way as mentioned earlier) is growing rapidly. Manufacturers such as Warren Buffett’s BYD, BAIC, and Volvo-owner Geely is putting a lot of effort in CEV development with the government subsidising CEV manufacturers since the government is betting that CEVs will solve the smog-problem in big cities across the country (Alestig & Hjalmarson-Neideman 2017). Even though the government is reducing the subsidies (due to a number of corrupt CEV start-ups), subsidies are likely to remain high for the big CEV manufacturers (such as BYD, BAIC and Geely) as the Chinese government has an ambition to sell 3 million CEVs per year by 2025 (Bloomberg News 2016).

3.1.3 Charging of Electric Vehicles

An ever debated problem with the transition to CEVs has been the required infrastructure, namely charging stations. The debate has two primary dimensions - 1) access to charging stations (i.e. the number of charging stations) and 2) time to charge (i.e. power output of the charging stations). Both these dimensions are something that have seen significant improvements just in the past years.

Access to charging stations seems to be less and less of an obstacle when considering buying a CEV. Japan, for example, now has more charging stations than petrol stations, although many are private (McCurry 2016). According to Uppladdning.nu (2016), there are currently around 30 stations in and nearby the town of Uppsala (compared to 250 in Stockholm). These charging stations all have at least one charging plug but can have up to ten plugs. If looking at the entire Uppsala County there are 41 charging points as of March 2017 and
this is only counting the public charging points (Laddinfra 2017). Overall there are 2,756 public charging points in Sweden and the most common power type is 3.7 kW (41%) followed by 22 kW (21%) (Laddinfra 2017). A noteworthy new regulation, that will affect charging of CEVs, is the new EU directive that will require new and refurbished houses to sport charging stations for CEVs. This directive is expected to come into effect 2019 (Neslen 2016). On a more local level, Sweden has decided on charging with mode 3 and type 2-plug as standard at all public charging stations, with start 2017. This will be of great importance for CEV retailers since lack of a joint standard have been holding back the spread of CEVs in Sweden (Svensk Energi 2013).

**Time to charge** a CEV has been seen as one of biggest problems when moving to an electrified car fleet. Mainly because refueling a fossil fuel driven car takes only a couple of minutes while recharging a CEV has historically taken at least a couple of hours. The slowest charging alternative currently being used, is that which corresponds to the power available in a normal socket. In Sweden this is 230 volts and 10 ampere, thus 2.3 kW of available power. The available charging options today are many in the range 2.3 kW - 145 kW (see Table 1 for more detail on today’s charging options). In order to make charging of CEVs less of an issue, BMW, Daimler’s Mercedes, Ford, and Volkswagen are, in a joint venture, exploring the possibilities of a 350 kW charger. More than twice that of Tesla’s supercharger of 145 kW. A 350 kW charger would recharge a 100 kWh battery in under 20 minutes (Lambert 2016).

Important to mention when talking about the time to charge, is how the charging power supplied to the battery varies with different factors such as size, supplied power, temperature, etc. According to Tollin (2016), the power supplied to the battery varies drastically with the State of Charge (SOC) of the battery when charging at high power. At high power the battery will receive the stated power only at a low SOC, but then the supplied power eventually decline as the SOC increases. At approximately 35-80% SOC (depending on the supplied power), the charging power will drop fairly linearly, as seen in Figure 11. According to Tollin (2016), even factors such as the condition of the battery (inner
resistance that change over time) and the temperature of the battery at the start of charging, can effect the rate at which the battery charges. However, at lower charging power (at about 10 kW or lower) the power can be assumed to remain constant, independent of the SOC of the battery (Tollin 2016).

<table>
<thead>
<tr>
<th>Type of charging</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charging using regular socket, 2.3, 3.7 or 7.4 kW</td>
<td>AC with 230 V and 10, 16 or 32 A fuse, charging power is constant regardless of the SOC</td>
</tr>
<tr>
<td>Charging using a 'Home Charging Station', 11 or 22 kW</td>
<td>AC 3-phase with 400 V and 16 or 32 A fuse, used both at home and at selected parking lots. Charging power starts to decline at around 95% and 80% SOC for 11 kW and 22 kW chargers respectively</td>
</tr>
<tr>
<td>Fast charging, 43 kW</td>
<td>AC 3-phase with 400 V and 63 A fuse, often used at gas stations, charging power starts to decline at around 70% SOC</td>
</tr>
<tr>
<td>Fast charging, 50 kW</td>
<td>DC 400 V with 125 A fuse, often used at gas stations, charging power starts to decline at around 60% SOC</td>
</tr>
<tr>
<td>Tesla supercharger, 125 kW</td>
<td>Tesla’s own technology, only available for Tesla cars, charging power starts to decline at around 40% SOC</td>
</tr>
</tbody>
</table>

Table 1: Different charging options (Emobility 2017)

From Table 1 it can be noted that charging at low power (2.3 or 3.7 kW) should be enough for the everyday usage of CEVs. 2.3 kW gives 115 km of distance charged in 10 h (assuming 5 km per kWh driving distance). This should be more than enough considering charging over night and given the average driving distance of 34 km per day (more on driving patterns in Section 3.2).

When discussing charging of CEVs there are mainly two different types of charging that are mentioned, Home Charging and On-the-Go Charging. Home Charging is more commonly done in households where as On-the-Go Charging cane be done at gas stations, rest-stops, restaurants, stores or other locations that would want to offer the opportunity to charge CEVs. Usually On-the-Go Charging is done at a higher effect, enabling more charging power in a shorter time.
Figure 11: Charging power of a BMW i3 vs battery SOC. Different colours represent charging at different days and charging stations (Electrify Atlanta 2017)

Grahn (2014) has categorized the type of charging strategies or typologies according to Uncontrolled Charging (UCC), External Charging Strategies (ECS) and Individual Charging Strategies (ICS). These are described further bellow.

**Uncontrolled Charging** means that the owner of the CEV will charge without a third party incentive / input or individual strategy. The owner will charge according to its charging behaviour however without the driver being influenced by certain parameters (see below).

**Individual Charging Strategies** means that the owner of the CEV will charge based on or influenced by, certain factors affecting the owner’s charging behaviour. This could for example be an owner that is price sensitive, thus choosing to charge during low price hours. Or a driver choosing certain routes to accommodate for charging at a certain station.

**External Charging Strategies** means that the owner of the CEV will charge based on what a third party dictates. This could for example be letting Vattenfall choose when the CEV should be charged based on the current and future strain on the grid.
In this study, Home Charging and Uncontrolled Charging will be assumed as the choice for all charging. This to focus the potential impact on the grid at a residential level. As for charging strategy, primarily ECS will be considered as a possible solution to the impacts that CEVs could have on the grid.

3.2 Driving Patterns

This subsection accounts for current data and research in modelling driving patterns that will be used in this research, both at a national level but also especially for Uppsala.

3.2.1 Modelling of Drive Patterns

As mentioned in Section 2, a part of this research will be to analyse and use data on driving patterns from data collected by LSP and TSS. The main project from TSS that will be used is the one called Bilrörelsedata 1 (BRD 1) that was commenced in 2010. The project has a final report written by Karlsson (2013) (in this section referred to as, the study) and was conducted in Västra Götaland (VG), Sweden, with GPS-tracking of over 700 ICE cars.

In the study, the goal was to gather data of 500 different vehicles for 30 days or more. In the final report it is stated that data from 714 cars was logged in the database. 528 cars logged data for more than 30 days and 450 cars logged data for more than 50 days (Karlsson 2013). The selection of cars was conducted by the
Swedish motor-vehicle register from cars matching the criteria in Table 2. Requests were sent out randomly to owners with cars that matched the criteria. In total the study received 932 positive responses from a total of 12,357 inquisitions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Chosen selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle type</td>
<td>Passenger car of type 1(^1)</td>
</tr>
<tr>
<td>Usage</td>
<td>Non-commercial</td>
</tr>
<tr>
<td>Model year</td>
<td>2002 or newer</td>
</tr>
<tr>
<td>Geographic area</td>
<td>Registered in VG county or Kungssbacka municipality</td>
</tr>
</tbody>
</table>

Table 2: Selection of cars in BRD 1

At the start for the study, the area in which the selection of cars was made consisted of approximately 17% of the total number of cars in Sweden and 17% of Sweden’s inhabitants. Average driving distance and cars per 1,000 inhabitants had almost a one-to-one ratio between the chosen area and the Sweden average (Karlsson 2013).

To be able to log the movement of the cars the study chose to use a GPS logger with a GSM modem and a memory card to be able to store data. The device (MX3 from Host Mobility) was connected to the 12V outlet in the cars. Some of the logged data include:

- Device (i.e. Car)
- Trip ID
- Final velocity
- Average velocity
- Distance
- Pause before & after
- Duration
- Start and stop date & time

The data was then collected by TSS and analyzed for errors that were removed upon finding (e.g. trips with speed under 0.1 km/h for more than 10 min) (Karlsson

\(^1\)A car that is mainly used for person transport and that holds the maximum capacity of 8 people (including the driver) and with a maximum weight of 3.5 tons
2013). From the database the study was able to analyse the results and draw conclusions regarding, e.g. number of trips per day and length per trip. For more details regarding the study contact TSS and LSP. There are some remarks on this study that need to be mentioned, these are stated below

- The data used in this research is slightly different from the one used in the final report by Karlsson (2013). This because since the final report was completed, TSS has made some small additional corrections in the database.
- Some data points have mistakes in them and have to be manipulated in order to be useful (see Section 4 on how this was done)
- There are some delays in when the GPS tracker starts, giving a different location on the start of a trip versus where the last trip ended. This delay varies and is in the final report accounted for by removing certain data points. After adjusting for loss of data, 460 cars with data logged for more than 30 days remained (compared to 528).
- The author of the study states that one disadvantage with tracking only through GPS is that the reason behind the trip is not recorded.
- The author of the study claims that driving patterns of the cars in the study might not be equal that of future CEVs, due to big difference in range. This is something that this report disagree with, partly due to the rapid advancements made in CEV range but also due to the average driving distance per day being significantly under the maximum range of the CEVs that already exist today (more of this in Section 5).

3.2.2 Seasonal Influence on Driving Patterns

According to Börjesson (2017) at Centre for Traffic Research (CTR), an important factor when analyzing driving patterns is the seasonal variation. Seasonal variation means that there are differences in people’s driving behaviour depending on the time of year.

One way to estimate the seasonal variation is by looking at the registered congestion charge of cars (trängselskatt). This gives a good overview of how many trips are made on a monthly basis. It should be noted that a trip in this sense is defined
by a car passing the point of registration and being registered for payment in the system. According to the study the seasonal effects are significant when modeling driving patterns. These differences are presented in Figure 12.

![Normalized Index of Number of Trips Taken](image)

**Figure 12: Index of seasonal change in driving patterns according to registered congestion fees** (Transportstyrelsen 2017)

Notable from Figure 12 is that there are most registrations of cars during the time April to June and that there is a significant difference compared to the number of registrations during the winter months (November to February). More on how seasons affect driving patterns and how this will be taken into account in Section 5

### 3.2.3 Driving in Uppsala Municipality

When looking at driving patterns on a specific regional level (Uppsala), there is little available information. The primary source of national driving statistics is Trafa. As mentioned in Section 2, Trafa gathers and presents statistics on the traffic situation in Sweden, both at a national level and at a more local level (municipality being the highest level of detail). By gathering information from the odometer of vehicles (done at yearly inspections of all registered cars in Sweden) Trafa is able to present statistics of total driving distance over the past year (Transport Analysis 2017a).

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2No congestion fee is taken in July
According to the latest Trafa compilation by Myhr (2016b), the average driving distance of a car in Sweden was 12,240 km per year (2016). The distance however varies depending on where in Sweden you live and in Uppsala the same number was 12,570 km per year, thus slightly above average (Myhr 2016b). Per day, these figures give an average driving distance of 33.5 km and 34.4 km per day respectively for Sweden and Uppsala. When looking historically, the average driving distance in Sweden has been more or less constant since 2005 (12,980 km) (Myhr 2016b).

To be able to make reasonable assumptions regarding driving patterns in Uppsala, demographic statistics of inhabitants and their behavior is needed. Uppsala Municipality (the office of Kommunledningskontoret) provides this information upon request in from of Excel sheets (SCB 2016b). Some key insights form this data is regarding inhabitants, number of households and number of cars per households. The data on the above mentioned is given on detailed geographic level, providing the opportunity to make high quality assumptions on where there will be a big impact from CEVs. The following data points were given per area in Uppsala Municipality, as of December 31st 2015 (SCB 2016b).

- Number of cars
- Number of houses and apartments
- Number of inhabitants
- Number of people working within/outside the area
- Average income

3.3 The Electric Grid

This subsection will account for the background information that is needed to understand how the electric grid in Sweden and Uppsala works and what implications there are to load variations.

3.3.1 The electric grid in Sweden

In 2011, Sweden was divided into 4 electric grid areas where Uppsala Municipality is a part of the third area, SE3. The division of the grid was a result of the
European Commission’s accusation that Sweden’s transmission regulations were discriminating to foreign costumers (Svensk Energi 2016b). The electric grid in Sweden is also divided into different levels according to local grid, regional grid and national grid, where the number of actors are by far the most on the local grid level with approximately 160 actors (Svensk Energi 2016a). On the regional grid there are three major actors (E.ON Elnät Sverige AB, Vattenfall Eldistribution AB and Ellevio AB) and the national grid only has one owner, Svenska Kraftnät (SVK) (Kjellman 2007). See Figure 13 for a break-down of the electric grid in Sweden.

The grid in Figure 13 is divided into transmission grid and distribution grid. The distribution grid in Sweden is what is refereed to as the local grid, where the transmission grid both consists of regional grid (110 kV) and national grid (265-275 kV).

According to Svensk Energi (2016a), the Swedish grid has a delivery reliability of 99.98% and on average the capacity of the grid and its transformers is well above the consumed load (Tollin 2016).

3.3.2 Current Load

Traditionally, the household load of consumed electricity has a relatively consistent pattern. People wake up, turn on e.g. their coffee maker and the load increases, go to work and the load decreases, come home and start to cook food and turn on other electric appliances which makes the load increase again, and then they go to sleep and the load decreases. The household load is driven by human behaviour and other factors such as the weather (especially affecting the need for heating).

Sweden

In 2015 the total usage of electricity in Sweden was 136 TWh. This was the second lowest usage in the 21\textsuperscript{th} century (mostly due to warm weather and thus low heating needs). Roughly 50\% of the electricity was used in the sector households and services and 37\% was used in the industry. The net export of electricity was record high in 2015 with 22.6 TWh being exported. (Andersson & Arvidsson 2016)

According to Byman (2016), the electricity usage in Sweden has been fairly con-
sistent at around 130-140 TWh per year for the last 25 years. This is due to more energy efficient appliances in households and machines in the industry have been able to make up for a growing population and an increasing number of households (Byman 2016).
On average, the home usage of electricity per person in Sweden was around 3.1 MWh in 2015, with variations in the northern parts of Sweden 4.2 MWh per person) and in the southern parts (2.6 MWh per person) (SCB 2016a). In Figure 14, a daily average electricity load profiles for houses and apartments are presented.

![Average daily load profile in Sweden](image)

Figure 14: Average daily load profile in Sweden (The Swedish Energy Agency 2010)

The load curves follow the behaviour described above. The time between 18:00-19:00, what is normally referred to as Peak Hour, is when the load is highest during the day.

When looking at a more granular level, there is a need to, not only divide electricity usage by type of household, but also by month and day. This since there is great variation in electricity usage over the year. Through The Swedish Energy Agency and the so called Hushällseldatabasen, this information is distributed upon request, by signing an agreement not to hand out the raw data to others. The data consists of measurements done in both detached houses and apartments over a longer period of time and the data includes the different electrical devices there are in a household. (The Swedish Energy Agency 2010)

The database consists of 201 households of the type detached house (single building with own supply of energy) and 188 households of the type apartment (a household that is part of a bigger building with mutual heating and water supply.
for all the households in the building). The database consists of over 200 million data points and can give a comprehensive overview of how electricity is used in Sweden. The different households that are measured are selected from a wide range of demographic groups and vary in size, number of inhabitants and income. Some of the households in the database are measured on a monthly basis and some on a 12 month basis. The measurements are done with 10 minutes intervals and stretch from 2005 to 2008. (The Swedish Energy Agency 2010)

According to Niklas Notstrand, Principal Statistician at The Swedish Energy Agency, there are some problems with the database. However, these problems mainly refer to statistical insignificance when using the database on a detailed level such as ’do apartments less 100 square meters, with 3 or more inhabitants, use more warm water than on average?’’. In a report by Zimmermann (2009), these types of questions are attempted to be answered where various results of electricity usage in Sweden are determined based on the data from Hushållseldatabasen. However, in these detailed cases / questions, the database is not comprised of enough samples to be able to provide statistically significant results and thus be representative for Sweden as a whole (Notstrand 2016).

There is also a somewhat skewed geographical selection of the households. As stated by Zimmermann (2009), this database was, at the time of creation, by far the most comprehensive database of its kind in the world. The goal was to collect data from 400 households that was selected using statistics from Statistiska Centralbyråns (SCB), and this goal was achieved. However when some of the selected households declined the offer to participate, they were replaced with a group of overrepresented households from the area of Mälardalen, giving the database a geographic imbalance (Notstrand 2016).

However, according to Notstrand (2016), the database will still provide results of high statistical significance when used not to split the data points into several different sub-groups. When looking at how average total energy usage differ during the days and months of the year and only divide by type of household (house or apartment), the database will provide reliable results (Notstrand 2016).
**Uppsala**

In Uppsala Municipality, Vattenfall owns most of the local grid and owns the entire grid in the town of Uppsala, as seen in Figure 15. The black stripes in the area Björklinge represents electric grid that is not owned by Vattenfall. Besides that area, Vattenfall owns all of the grid inside the green line (representing Uppsala Municipality) as well as the majority of the grid in the closest outskirts of Uppsala Municipality. This means that Vattenfall are responsible for all power stations, on all levels, as well as transmission lines from the regional grid all the way to each household.

![Figure 15: Vattenfall’s grid in Uppsala County (Nätområden.se 2016)](image)

In Uppsala, the average home usage of electricity per person was 3.0 MWh in 2015 thus slightly below the national average (SCB 2016a).

3.3.3 Future load

As mentioned above, the electricity consumption has been relatively constant for the past 25 years. Kungl. Ingenjörsvetenskapsakademien (IVA) has recently completed a report on how the energy system might look beyond the year 2030. In that report, it is predicted that the electricity usage will be between 128-165 TWh annually. The report states that it is difficult to predict usage of electricity more than 5 years into the future and refers to previous projections that are usually accurate when
conducted only a couple of years in advance but tend to be further from reality when done with greater time scale. (Liljeblad 2016)

An increase to 165 TWh by 2030 is equal to an increase with 22% from today, or a yearly increase by roughly 4%. When breaking down the electricity usage it is done in three major segments, Housing and Service, Industry and Transport (Liljeblad 2016). Since this report focuses on how the electricity load in households will be affected by CEV growth, the predicted electricity usage in the Housing and Service segment, which includes electricity heating, is particularly interesting.

Housing and Service will have a usage of 65-85 TWh, compared to today’s usage of 71 TWh. The biggest increase is predicted to be in the service sector (30-40 TWh compared to 31 TWh today) due to an increased demand in service related products. An increase in e-shopping is predicted to lead to a growing number of warehouses that will need more electricity than the reduced need in regular stores. The household electricity is predicted to be at 20-25 TWh, compared to today’s usage of 21 TWh and is largely dependent on the predicted increase in population (and number of households). Energy efficient appliances and new technology is predicted to hold back the usage need. Finally, the required need for electric heating is predicted to be lower in 2030 (15-20 TWh compared to 19 TWh today). This is due to a warmer climate and more efficient heating system (larger share of heat pumps that have a high efficiency).

Assuming a 'worst case' scenario with electricity heating remaining constant at 19 TWh and household electricity increasing from 21 to 25 TWh gives a yearly increase of approximately 0.79% and a total increase with 12.5% until 2030. In areas where heating is supplied from other sources than electricity (e.g. district heating) the relative change will be even greater assuming that the grid in these areas are not dimensioned for the heating supply. These areas will see a 19% increase until 2030 or a 1.2% annual increase, in a 'worst case' scenario. Noteworthy is that the increase in the Transport segment (which is predicted to be mostly due to growth of electric vehicles) is separate and thus not accounted for in the Housing and Service segment.

Overall Liljeblad (2016), mentions four major factors to how much and how fast
the electricity demand will change within the different segment above. These are:

- Economical development
- Population growth
- Technical development
- Political decisions and regulations

Examples of these factors is GDP development, price on batteries, migration and subsidies. Figure 16 presents different scenarios of electricity usage depending on the population in Sweden. It is notable that the differences are substantial (up to 40 TWh difference), indicating that these future projections are hard to get right.

![Figure 16: Projected electricity usage depending on different population scenarios (Byman 2016)](image)

When looking at the change in electricity demand until 2030, there is also a need to look at the effect (the peak demand). This is because it is the peak demand that determines the dimensioning of the electric grid (Persson 2016). Until 2030 the peak demand is not predicted to see any drastic changes from the expected overall increase in electricity usage. According to Byman (2016), this is because the peak demand is expected to grow parallel to the electricity demand. The areas where there might be a change in peak demand is electricity heating and transport. This is because the demand in heating might be lower, thus reducing the peaks during winter, and that a electrified passenger car fleet might be able to shift the peak to other off-peak periods during the day (Byman 2016).
3.4 Previous Research

In order to make sure that this thesis will contribute to science and the general research in this area, different studies that have been conducted in similar fields as this report will be examined. This to confirm that the research questions in this report have not yet been answered. This subsection presents the findings.

3.4.1 Research study #1

This research was conducted in 2013 as a PhD thesis at Royal Institute of Technology, Stockholm.

The purpose of the thesis was to complete certain knowledge gaps in the area of how CEVs will impact the grid load. The aim was to investigate the impact of different types of electric vehicles charging on load profiles and load variations in Sweden.

The thesis uses a stochastic model based on transport and load data to be able to simulate how charging of CEVs would affect the load given five different charging scenarios.

The thesis establishes that there are three key factors that determine how the load will be affected. These are charging location, charging need and charging moment. The thesis also establishes that the model gains accuracy as the quality and amount of data increases.

The results of the thesis indicate that during ‘unoptimized’ scenarios, with full adaption to CEVs, there can be significant increases in peak load. (Grahn 2013)

3.4.2 Research study #2

This research was conducted in 2011 for the Institute of Electrical and Electronics Engineers, New York.

This study aims to model and analyze the demand of grid load in a distribution system due to battery charging of electric vehicles. The study is conducted on a distribution system in the United Kingdom and uses a stochastic formulated method and different charging scenarios to model how the load is effected. The study
simulates four charging scenarios, with and without optimized smart-charging, and different types of batteries with different needs.

One conclusion from the study is that with a CEV market share of 20%, the daily increase in the load will be 36% in a 'worst-case' scenario. (Qian et al. 2011)

3.4.3 Research study #3

This research was published in Elsevier in 2008 for their Transport and Environment section.

This study models driving patterns and identifies driving cycles in large Chinese cities. The study presents a method to collect data by a so called car-chase technique and by identifying the most important factors in drive patterns.

The study indicates that among the important factors that define driving patterns are local road infrastructure and driving behaviour. (Wang et al. 2008)

3.4.4 Research Study #4

This study was conducted in 2015 for the Electrical Engineering School as a master thesis at The Royal Institute of Technology.

The study was done in collaboration with Ellevio with the purpose to investigate how many CEVs that can be charged at the same time in different areas in Stockholm.

The study uses a standardised charging case (effect and time), combined with internal knowledge on grid components capacity and load for five different areas in Stockholm, to determine at what percentage of the areas’ parking lots the charging could cause a problem.

The study finds that cable overload could cause a major problem due to CEVs charging and that the areas that are most vulnerable are rural areas with small houses. The study also finds that much of the problem can be solved by giving the consumers the incentive to charge at night. (Persson-Gode 2016)

3.4.5 Conclusion from previous research

From the research studies the following conclusions can be drawn:
• It is a reconfirmation that the research questions in this report are valid and in need of answers
• In the existing research on CEVs’ impact on the grid, focus is not on actual driving patterns and driving behaviour
• There is a need to conduct this type of study with a higher level of granularity, i.e. Uppsala Municipally instead of Sweden and the U.K
• Several of the studies focus on the Effect from different types of charging strategies
• The theses uses data input and sources that can possibly be re-used in this thesis or at least be used as inspiration to where and how data can be found and generated
• Only one of the theses focus on how the distribution and transmission capacity of the electric grid are affected by CEVs. The other focus on load profiles in general and production related issues
• None of the theses have a future approach regarding CEV development, future electricity usage and the future mobility need

3.5 Summary of Literature Review

The literature review conducted in this report will, as mentioned in Section 2, serve as a frame of reference when completing this research. The theory in Section 3.1 will help making projections on the CEV market development in Sweden and Uppsala as well as provide the needed technical knowledge regarding charging and battery capacity. Section 3.2, will help provide data sources and modelling techniques for driving patterns in order to create a model to simulate driving patterns in and around the Uppsala area. Thirdly, Section 3.3 gives the necessary knowledge to incorporate the modelling of driving patterns to existing load curves. It also helps understanding how the electric grid might be affected by CEVs and what actions is needed to account for this. Finally Section 3.4 ensures that the research is relevant and that the MRQ is correctly formulated. Bellow are the overall key take aways from the conducted literature review.

Firstly, the literature review establishes what is well-known, namely that the
CEV market is seeing explosive growth based on sales figures, car manufacturer’s strategic planning/investments and developments in charging technology.

**Secondly,** the literature review helps to understand how driving patterns will affect the need and character of CEV charging and how this can be modeled.

**Thirdly,** the literature review provides the initial background information required in order to understand how load variations impact grid infrastructure.

**Finally,** the literature shows that previous research conducted in this area needs to be supplemented, which confirms that the research questions in this study are valid and in need of answers.
4 CEV projections 2030

This section accounts for all the projections that have been made using the data described in Section 2 and presented in Section 3.1. The assumptions and calculations that have been made are accounted for in this section. This section finally presents the findings regarding development of CEV models in the world as well as projections of CEVs market share in Sweden and in Uppsala.

4.1 Assumptions

When conducting the different projections in this section, some assumptions had to be made. These assumptions are presented in Table 3.

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Description</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continued growth</td>
<td>The growth of CEV sales is assumed to continue at a similar pace as it has between between 2012 and 2016</td>
<td>It is reasonable as long as the influencing factors are the same. Such as politics, economics, etc.</td>
</tr>
<tr>
<td>Declined growth</td>
<td>Even if sales are assumed to continue to grow, it has been assumed that the growth rate will decline to 30% between 2017 and 2022</td>
<td>The CAGR between 2013 and 2016 was 207% thus, 30% is an understatement for at least the first couple of years of the projection</td>
</tr>
<tr>
<td>Price parity</td>
<td>According to Randall (2016), it is assumed that CEVs will reach price parity with ICEs in 2022</td>
<td>Randall (2016)</td>
</tr>
<tr>
<td>Dramatic shift</td>
<td>After 2022 it is assumed to be a dramatic growth in CEV sales due to price parity being reached and that all new cars that are sold will be CEVs within three years</td>
<td>Assuming all else stays the same, there will be no reason not to buy an CEV. Also if price parity is reached, governments can more easily work towards completely banning sales of ICEs</td>
</tr>
</tbody>
</table>
Scraping of CEVs is not taken into account since there are no current figures of this available. Though it is reasonable to believe that some of the early bought CEVs will have to be replaced by 2030.

Since a car is owned on average 14 years before being scraped or deregistered it is unlikely that a significant number of CEVs will be scrapped before 2030 (Transport Analysis 2017a).

It is assumed that sales of EVs in Uppsala will increase proportionally to the rest of Sweden.

Uppsala is currently following the sales trends of Sweden as a whole and it is deemed reasonable that it will continue to do so. See Section 3.1 for further details.

<table>
<thead>
<tr>
<th>Scapping</th>
<th>Uppsala</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scapping of CEVs is not taken into account since there are no current figures of this available. Though it is reasonable to believe that some of the early bought CEVs will have to be replaced by 2030.</td>
<td>It is assumed that sales of EVs in Uppsala will increase proportionally to the rest of Sweden.</td>
</tr>
<tr>
<td>Since a car is owned on average 14 years before being scraped or deregistered it is unlikely that a significant number of CEVs will be scrapped before 2030 (Transport Analysis 2017a).</td>
<td>Uppsala is currently following the sales trends of Sweden as a whole and it is deemed reasonable that it will continue to do so. See Section 3.1 for further details.</td>
</tr>
</tbody>
</table>

Table 3: Assumptions made when making CEV projections

4.2 Calculations

In this subsection the calculations that where used when conducting the different projections are presented. The calculations that were made were:

- # New Cars 2017 - 2030, for both Uppsala and Sweden
- # Cars in Traffic 2017 - 2030, for both Uppsala and Sweden
- # New CEVs 2017 - 2021, for Sweden
- # New CEVs 2022 - 2030, for Sweden

These are the 4 main calculations with associated assumptions that were made in order to make the projections. Further these simple calculation(s) were made:

- # New CEVs for Uppsala - was estimated from the calculations on # New CEVs done on a national level and then scaled down proportionally to apply to Uppsala

4.2.1 # New Cars 2017 - 2030

To calculate the number of new cars each year between now and 2030, the yearly CAGR (Compound Annual Growth Rate) was retrieved for the years 2006 to 2016.
(Myhr 2016a). This was done as shown in Equation 1

\[
\# \text{ New Cars CAGR} = \left( \frac{\# \text{ New Cars 2016}}{\# \text{ New Cars 2006}} \right)^{\frac{1}{2016-2006}}
\]  

(1)

Further, the succeeding years were calculated by multiplying ‘\# New Cars 2016’ with the ‘\# New Cars CAGR’, compounded by the number of years surpassing 2016. For example, \# New Cars 2020 was calculated according to Equation 2

\[
\# \text{ New Cars 2020} = \# \text{ New Cars 2016} \times \# \text{ New Cars CAGR}\textsuperscript{2020–2016}
\]  

(2)

4.2.2 \# Cars in Traffic 2017 - 2030

To calculate \# Cars in Traffic 2017 - 2030, the same equation as in the previous section was used. This is shown in Equations 3 and 4

\[
\# \text{ Cars in Traffic CAGR} = \left( \frac{\# \text{ Cars in Traffic 2016}}{\# \text{ Cars in Traffic 2006}} \right)^{\frac{1}{2016-2006}}
\]  

(3)

\[
\# \text{ Cars in Traffic 2020} = \# \text{ Cars in Traffic 2016} \times \# \text{ Cars in Traffic CAGR}\textsuperscript{2020–2016}
\]  

(4)

4.2.3 \# New CEVs 2017 - 2021

To calculate \# New CEVs per year between 2017 - 2021, the previous year’s \# New CEVs per year is multiplied by 30%, as assumed. This is shown in Equation 5.

\[
\# \text{ New CEVs year } X = \# \text{ New CEVs year } (X-1) \times (1 + \text{30\%}), \text{ where } 2017 \leq X \geq 2021
\]  

(5)

4.2.4 \# New CEVs 2022 - 2030

To calculate \# New CEVs per year 2022 - 2030, it is assumed that CEVs will reach 100% market share within 3 years. This means that all New Cars 2024 will be CEVs. The market share 2021 has been calculated to roughly 13%. The market share is therefore estimated to be 40% in 2022 and 80% in 2023.
4.3 Findings

This subsection will present the findings on CEV development both for Sweden as a whole as well as for Uppsala Municipality. The subsection also includes a compilation of CEV models.

4.3.1 Model development

Figure 17 illustrates the development (both historic and planned) of BEV models from some of the biggest car manufacturers in the world (excl. Asia) from 2010 to 2020.

It is notable that the development is moving towards CEVs with longer range, closing in on the range of conventional cars which is seen as one of the bigger reverse salients for the market expansion of CEVs. The new models presented in Figure 17 are only some of the announced models to be presented and as shown they are all expected to be on the roads by 2020.

There are currently no press releases or news confirming models being released after 2020, most likely due to the current planning span of car manufactures being up to fours years into the future.
4.3.2 Sweden

The projections indicate that Sweden is on track to reach 10% CEVs of new sales in 2020, and 1 million CEVs in traffic by some time during 2024. These projections can be seen in Figure 18 and Figure 19.

![Figure 18: Projection of the number of CEVs in Sweden](image1)

![Figure 19: Projection of the market share of CEVs in Sweden](image2)

The projections suggest that 4 million CEVs are projected to be in traffic by the year 2030 and that Sweden in total will have 5.7 million cars in traffic. The
projec^ons for Sweden can be seen in its entirety in Table 11 and Table 12 in Appendix B

4.3.3 Uppsala

Following the projections for Sweden and the historic figures of CEV development presented in Section 3.1, projections for Uppsala Municipality can be presented in Figure 20 and Figure 21.

![Figure 20: Projection of the number of CEVs in Uppsala Municipality](image)

By 2030 approximately 71,000 cars will be chargeable in Uppsala Municipality, making CEVs account for roughly 73% of the total number of cars in the municipality. The total number of cars in traffic in Uppsala Municipality is expected to be 97,000 cars by 2030. The projections for Uppsala can be seen in its entirety in Table 13 and Table 14 in Appendix B.
Figure 21: Projection of the market share of CEVs in Uppsala Municipality
5 Analysis of Driving Patterns 2030

In this section the analysis of the gathered data on driving patterns is presented. The section describes the assumptions and calculations that have been made and presents the findings from the analysis.

5.1 Assumptions

To be able to use the TSS database in a way that is useful to this research, some assumptions, corrections and simplifications have been made, these are presented in Table 4.

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Description</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day of week aggregation</td>
<td>When aggregating the data, it is chosen not to distinguish between the days of the week <em>between different</em> weeks of the month. Thus, the first Monday in January is not distinct from the second Monday in January, and so on</td>
<td>There may be some extremes that are averaged out due to this assumption. However, those extremes cannot be pinpointed in this database either way as the database size is to small. Thus, these extremes will have to be simulated in a sensitivity analysis instead</td>
</tr>
<tr>
<td>Data cleansing</td>
<td>Errors were corrected in line with the study by Karlsson (2013). Trips with a stop under 10 seconds were made into one trip. All trips with under 0.1 km/h speed for more then 10 minutes were discarded. Data from before 2005, after 2014 and all duplicates were discarded</td>
<td>It is reasonable to make some point incisions in databases of this size. Guidelines provided by (Karlsson 2013) were used</td>
</tr>
</tbody>
</table>
No distinction between cars

The TSS database provides the data tag 'Device' which allows to separate each analysis on a car by car basis. However, to deal with a bigger sample size each car is treated anonymously and on an aggregated level.

Given that the sample size consists of 39,700 days of which the car was registered and roughly 700 vehicles, most major deviations should be averted.

Unchanged driving behaviour

The data in the TSS database is from 2010 but the assumption is made that driving patterns will not change significantly by 2030.

Available data on driving distances indicate that driving distances have been relatively unchanged since 2005 as described in Section 3.2. Thus the evidence points toward consistent driving habits, but it is not conclusive. ³

Table 4: Assumptions made when analyzing TSS data and modeling driving patterns

### 5.2 Calculations

The data that was acquired consisted of the following data points (as described in Section 3.2.1):

- Device (i.e. Car)
- Trip ID
- Final velocity
- Average velocity
- Distance
- Pause before & after
- Duration
- Start and stop date & time

The following calculations had to be made in order to aggregate the database into numbers that could be used to produce the findings in the next section.

³Note that there are few studies on how driving habits have changed and the few studies that do exist are on an aggregated level.
5.3 Findings

This subsection presents the findings found from compiling the TSS database. The findings are presented as figures, showing variations in driving distance and stopping time of vehicles.

5.3.1 Driving distance

Figure 22 shows that the most frequent average distance driven per day (including days where no driving occurs) is 25 to 30 km per day. The average in Figure 22 is 38.0 km per day per vehicle however this assuming each car was under registration for equally many days. Taking into account the fact that the monitored cars were not tracked for equally many days, the calculated weighted average distance per day per vehicle is 32.4 km.

Figure 23 shows that the driving patterns vary with the days of the week. It shows that there are significantly fewer trips made during the weekend as well as less distance driven. The peak driving day in terms of distance driven is Thursdays at 35.1 km per day as opposed to the day with the least distance driven, Saturdays at 28.1 km. The number of trips made per day overall correlate with the distance
travelled per day, with a small discrepancy on Sundays where the distance per trip is lower than average, as shown in Figure 23.

Figure 24 shows that the monthly variations in terms of both driven distance as well as number of trips per day vary with the months of the year. The data points to a higher driving activity during the summer months of May to July and a lower driving activity in April, August, September and October. The number of trips taken per day correlates well with the driven distance per day.
Figure 24: Monthly variation in driving patterns. Data provided by Test Site Sweden (2017)

5.3.2 Final stopping time

Figure 25 shows that there is a peak of cars arriving home (presumably) between 16:00 and 19:00. The data is aggregated from a sample of 39,700 unique cars & days and on 10 minute intervals. Thus, the peak of 1.6% at 18:00 translates to 1.6% of any given sample. This means that if there are 1,000 cars in an area, this data suggests that 16 cars would arrive home between 18:00 and 18:10.

Figure 26 shows that there are variations in what was presented in Figure 25, when it comes to the day of the week. Figure 26 indicates that the last stop of the day varies between weekdays and weekends. There is a smaller peak and lower concentration of the number of vehicles that make their last stop of the day during weekend than during the weekdays. The difference between the peak on Tuesdays (highest weekly peak) and Saturdays (lowest weekly peak) is 75% (with Tuesdays having a 75% higher peak than Saturdays). Figure 26 also shows that looking at each day of the week separately compromises the number of data points available to produce the histogram, resulting in less 'smooth' histograms. Given that the database in itself contains 39,700 days that can be considered and that there are 7 days in a week, there are on average roughly 5,700 data points per day of the week, that need to be mapped onto the 10 minute intervals of which there 144 in a day.
That means that there are on average roughly 40 data points per each 10 minute interval. Thus, the relative standard deviation is much higher as you inspect the data on a higher detail level. Or differently phrased, the sample size for each curve is a seventh of that which it is for the average.

Figure 26: Histogram of last stop of the day aggregated for per each day of the week. Data aggregated over 10 minute intervals. Data provided by Test Site Sweden (2017)

Figure 27 shows that there are variations in what was presented in Figure 25, when it comes to the month of the year. Figure 27 indicates that the last stop of
the day varies depending on which month of the year it is. Due to big variations it is difficult to see in Figure 27 which month has the highest peak of number of vehicles making their last stop of the day at the same time. However, from the calculation it can be extracted that the highest peak (December) is 47% higher than the lowest peak (April). Figure 27 also shows that looking at each month of the year separately compromises the number of data points available to produce the histogram, resulting in less ‘smooth’ histograms. Given that the database in itself contains 39,700 days that can be considered and that there are 12 months in a year, there are on average roughly 3,300 data points per each month, that need to be mapped onto the 10 minute intervals of which there 144 in a day. That means that there are on average roughly 23 data points per each 10 minute interval. Thus, the relative standard deviation is much higher as you inspect the data on a higher detail level. Or differently phrased, the sample size for each curve is a twelfth of that which it is for the average.

Figure 27: Histogram of last stop of the day aggregated for per each month of the year. Data also aggregated over 10 minute intervals. Data provided by Test Site Sweden (2017)

These findings derive from the raw data provided by TSS database and thus the findings are not Uppsala specific. This has been taken into account by looking at the average driven distance in Uppsala and compared it to the average driving distance in the TSS database. The average distance driven per day in Uppsala is
34.3 km and the average distance driven per day in the TSS Database is 32.4 km. Thus, the Uppsala average distance driven per data is roughly 6% more than in the TSS database. This will be taken into account in Section 6.
6  CEVs’ impact on the Uppsala grid 2030

In this section the effect on the electric grid from CEVs is presented. The section starts by looking at how the load varies during the day/year today, followed by an analysis of how the future share of CEVs will impact the household load.

6.1  Assumptions

To be able to use the database from The Swedish Energy Agency in a useful way and to adjust current data to future scenarios, some assumptions had to be made. These are presented in Table 5.

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Description</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistically significant</td>
<td>By aggregating the data in the database, a statistically big enough sample of houses and apartments can be obtained to be representative for households in Sweden.</td>
<td>This assumption is backed by Notsstrand (2016), and the fact that the average electricity usage per household in the database is close to the known average household electricity usage of Swedish households.</td>
</tr>
<tr>
<td>Future electricity consumption</td>
<td>To be able to determine how the electricity usage in households will be in 2030 (in order to compare with the CEV load 2030), projections on the development of electricity usage in households provided by IVA is used. These projections are used to adjust the created load curves from the database.</td>
<td>IVA is viewed as a reliable source due to their many publications and good reputation in the academic community. However, IVA also states that there is uncertainty in their projections.</td>
</tr>
</tbody>
</table>
The assumption that the electricity usage in Uppsala is the same as what is represented in the database is made to be able to apply the data to Uppsala. Since the database is deemed big enough to represent households in Sweden and since the average household electricity consumption in Uppsala is almost the exact same as the average for entire Sweden, this assumption is deemed as reasonable.

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Description</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICE = CEV</td>
<td>In the TSS database, logged vehicles were all ICEs. Thus, to make this data usable, it is assumed that CEVs will be driven same way that ICEs are driven today</td>
<td>Range of CEVs are projected to increase as to accommodate what is expected today. See Section 8 for further discussion</td>
</tr>
<tr>
<td>Charging starts at last stop and last stop only</td>
<td>It is assumed that all charging will be started precisely at the last registered stop of the day and that this stop is at home. It is also assumed that no charging is done before the last stop</td>
<td>That Home Charging would be the most common charging behaviour is deemed most likely as the charging technology available today can accommodate the charging needs in a standard socket (see Section 3.1.3). Heesterman (2017) also points out that a vast majority of customers start to charge when they arrive home. See Section 8 for further discussion regarding this</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>Charging speed</td>
<td>The assumption that all charging is done at home makes it reasonable to also assume that charging will not be done at high power (fast charging). Thus the average charging power is assumed at 3.7 kW. Since fast charging equipment is expensive and that 99% of all drivers will suffice with charging at low power during the night (see Section 3.1.3).</td>
<td></td>
</tr>
<tr>
<td>Uncontrolled charging</td>
<td>The assumption that all charging is done uncontrolled, i.e. without strategy from the owner or involvement from a third part is made (See Section 3.1.3). Without clear incentives and / or benefits there is little that motivate people to change their behaviour. This report also seeks to investigate the worst case scenario.</td>
<td></td>
</tr>
<tr>
<td>kWh per km</td>
<td>It is assumed that an average CEV can travel 5 km on one kWh. From a holistic perspective throughout the literature review this seem like a fair figure. It is also the current energy usage of the Nissa Leaf (Nissan 2016).</td>
<td></td>
</tr>
<tr>
<td>24-hour days</td>
<td>A simplification to segment the driving days to start at 00:00 and end at 23:59 is made. This creates the assumption that all trips starting after 00:00 end ending before 23:59 is done the same 'driving day', leaving an error when trips that start before 23:59 but end after 00:00 (the next day) The assumption is made to be able to handle the large number of data points and to be able to use the data in a productive way. Identifying the 'actual driving days' rather than the time-defined days would also be complex and possibly inaccurate. This possible error is discussed further in Section 8.</td>
<td></td>
</tr>
</tbody>
</table>
Always fully charged battery. The assumption that drivers always want to charge their battery to its fullest is made and thus the model simulates that drivers always recharge their battery after the last stop of the day.

This assumption is made for two reasons. Firstly because people want to be prepared for unexpected events where it might be necessary to have a fully charged car and thus it is believed that this will be the natural charging behaviour. Secondly, because if there are no incentives not to charge the battery to its fullest people will not care to spend effort and time to plan their charging behaviour. The possible error is discussed further in Section 8.

<table>
<thead>
<tr>
<th>Table 6: Assumptions made when combining data from TSS with the data from The Swedish Energy Agency</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.2 Calculations</td>
</tr>
<tr>
<td>This subsection presents the calculations that were used to assess CEVs’ impact on the grid. The calculations consist of three parts. Firstly, the calculations that were made in order to compile the data provided by The Swedish Energy Agency. Secondly, the calculations that were made in order to translate the impact of driving patterns (see Section 5) into a grid load that can be compared to the data provided by the Swedish Energy Agency. Lastly the CEV load needs to be adjusted to parameters that apply in Uppsala.</td>
</tr>
<tr>
<td>6.2.1 Calculations household load</td>
</tr>
<tr>
<td>The data that was acquired from The Swedish Energy Agency consisted of the following data points (as described in Section 3.3.2)</td>
</tr>
<tr>
<td>• Date &amp; time (per 10 minute intervals)</td>
</tr>
<tr>
<td>• Appliance identifier</td>
</tr>
<tr>
<td>• House identifier</td>
</tr>
</tbody>
</table>
• Energy consumed (per 10 minute interval)

The following calculations had to be made in order to aggregate the database into numbers that could be used to produce the findings in the next section. The calculations made are each on a average per household basis and have all been adjusted according to a 2030 scenario as described in Table 5.

• Retrieve and aggregate the consumed energy per each 10 minute interval of a day and for each household, per day of the week, for houses (Figure 28)
• Retrieve and aggregate the consumed energy per each 10 minute interval of a day and for each household, per day of the week, for apartments (Figure 29)
• Retrieve and aggregate the consumed energy per each 10 minute interval of a day and for each household, per month, for houses (Figure 30)
• Retrieve and aggregate the consumed energy per each 10 minute interval of a day and for each household, per month, for apartments (Figure 31)
• Retrieve the day of the week and the month of the year with the highest load peak, for houses and apartments (Figure 32)

6.2.2 Calculations CEV load

Given that the outcome of Section 5 is a 'when' and a 'how far', the only calculation that needs to be made to be able to map the driving patterns onto the household load, is to convert the 'how far' to a measurement of energy. This is done according to Equation 6. The adjustment to convert to distance driven in Uppsala is also made by multiplying the distance driven by the relative difference in distance, as mentioned in Section 5.

\[
\text{Distance travelled (km)} \times \text{Energy needed per distance } \left(\frac{\text{kWh}}{\text{km}}\right) = \text{Energy needed (kWh)}
\]

Further, to calculate when a CEV will be done charging, which is essential to calculating the load curves due to CEVs, Equation 7 translate the needed energy to time.
\[
\frac{\text{Energy needed (kWh)}}{\text{Charging power (kW)}} = \text{Time until fully charged (h)} \tag{7}
\]

Given the time until fully charged and the chosen charging power, the CEV load curves can be produced.

### 6.3 Findings

In this subsection all findings on CEVs impact on the electric grid are presented. That includes the findings on household load, driving patterns translated to charging need and the combined impact on the grid.

#### 6.3.1 Household load

By analysing the data in the database *Hushällsdatabasen* from The Swedish Energy Agency, the load curves in Figure 28 to Figure 32 are compiled. As the relevant Uppsala adjustments have been made, the findings of how electricity is being used, are Uppsala specific.

Figure 28 and Figure 29 show that there is a significant variation in power consumption between the days of the week, in both houses and apartments. Both figures show that the household load is fairly similar during the weekdays as well fairly similar during the weekend. Both figures also showcase a significant difference in the household load between weekends and weekdays. This difference is most likely explained by different energy related behaviours in the household that vary with the days of the week.

Figure 30 and Figure 31 show that there is a significant variation in power consumption between the months of the year, in both houses and apartments. Months with high power consumption are months in the winter (January and February) and months with low power power consumption are months in the summer (June and July). This is most likely due the need of more heating and lighting power during the winter months. The two figures also show that there is a bigger relative variation in houses than there is in apartments. This is most likely due the dependency that houses have on their heating systems.
Figure 28: Electricity load in houses per day of the week. Data provided by The Swedish Energy Agency (2010)

Figure 29: Electricity load in apartments per day of the week. Data provided by The Swedish Energy Agency (2010)

Figure 32 shows the worst case household load for both houses and apartments. The figures show that the peak load for houses occurs at 18:10 on a Saturday in January with a peak load of 6,193 W, and that the peak load for apartments occurs at 19:50 on a Saturday in March with a peak load of 1,549 W.
6.3.2 CEV load

By combining the analysis made on the TSS data (as presented in Section 5) with the assumptions and calculations regarding CEV charging the findings shown in Figure 33 to Figure 35 are obtained, illustrating the CEV load. The data presented shows the CEV load per CEV, thus the household type and number of vehicles per
Figure 32: Worst case daily usage of electricity. Data provided by The Swedish Energy Agency (2010)

household has not been taken into account. As the relevant Uppsala adjustments have been made, the findings are Uppsala specific.

Figure 33 illustrates how the load due to charging of CEVs differ during the days of the week. Figure 33 shows that the CEV load peak is higher during weekdays compared to weekends (approximately 920 W compared to 620 W) but that the peak occurs at roughly the same time. The highest peak (Monday, 940 W) is 71% higher than the lowest peak (Saturday, 550 W)

Figure 33: CEV load charging per day of the week
In Figure 34, the CEV load variation on a monthly basis is presented. Figure 34 shows a more even CEV load compared to Figure 33. A slightly higher load is noted during the summer months of June and July as well as during winter months of January and December, compared with the rest of the year. The highest peak (December, 996 W) is 47% higher than the lowest peak (April, 678 W). This suggests that the CEV load varies more with the days of the week than the months of the year since the highest to lowest peak difference is greater between the days of the week than for the months of the year. To be noted is that there are more data series presented in Figure 34 than Figure 33 making it harder to distinguish significant differences.

Figure 34: CEV load charging per month of the year

Figure 35 shows the worst case CEV load based on the TSS database. The peak occurs on a Friday in December at 18:30 and amounts to 1,330 W. This is significantly higher than what is presented in Figure 33 and Figure 34 supporting further that the peaks in CEV load varies with the months of the year and the days of the week.

6.3.3 Findings CEVs impact on the grid

This section will illustrate the findings that can be retrieved by combining the household load with the CEV load. This section also takes the number of CEVs
Figure 35: Worst case scenario of CEV charging during one day

into account with respect to the number of vehicles per household as well as share of vehicles that are CEVs.

Figure 36 shows household load in a house with the added CEV load. With the parameters that apply for Figure 36, the max peak is 6,131 W which is an increase of 12% compared to the max peak if considering only the household load without CEVs that day. With regards to the worst case max house load as shown in Figure 32 (Saturday, January), the peak in Figure 36 is 99% of the max load. This means that on a Monday in February, if there is a market penetration of 75% CEVs, with an average of 1 vehicle per household, the max load that is to be expected on that day will increase by 12%. It also means that, in this scenario, the previous worst case load was almost reached, but on a different day and month than before.

Figure 37 shows household load in an apartment with the added CEV load. With the parameters that apply for Figure 37, the max peak is 1,699 W which is an increase of 10% more than the max peak if considering only the household load without CEVs. With regards to the worst case max apartment load, shown in Figure 32, the peak in Figure 37 is 10% higher (the selected day and month coincides with that of the worst case scenario). This means that on a Saturday in March, if there is a market penetration of 25% CEVs, with an average of 0.5 vehicle per household, the max load that is to be expected on that day will increase by 10%. 
Figure 36: An average household load on a Monday in February in a house combined with an average CEV load. This assumes 1 vehicle(s) per household and a 75% CEV market penetration implying 0.75 CEVs per household. The day and month was chosen at random. It also means that, in this scenario, the previous worst case load was proceeded by 10%.

Figure 37: An average household load on a Saturday in March in an apartment combined with an average CEV load. This assumes 0.5 vehicles per household and a 25% CEV market penetration implying 0.125 CEVs per household. The day and month was chosen at random.
Given that the above data points can be extracted for each scenario of CEV market penetration and for a varying number of vehicles in a household, a model can be run to evaluate the impact on the grid from CEVs with the following parameters being changeable.

- Day of the week and month of the year for both the household data (apartments and houses) as well as the driving patterns data
- Share of CEVs
- Number of vehicles in apartments and houses in the different areas in Uppsala Municipality (provided by SCB (2016b))

Extracting and searching the for biggest increase in max peak load relative the previous max peak load (as shown in Figure 32), generates Table 7. Table 7 is a preview of the data points that were extracted. The table in its entirety can be found in Table 15 in Appendix C. Table 7 shows that the increase in max load increases almost linearly with the share of CEVs of cars in traffic. The table also shows that apartments are expected to see a bigger increase in max load than houses. Through this simulation, it can be found that Kungsängen is the area that is expected to see the highest increase in max load. This is true for all share of CEVs of cars in traffic 2030 scenarios. As this is on a household basis, the results correlates directly with the number of cars per household as showed in Table 16 in Appendix C. Using these results, simple case examples can be constructed, as shown in Figure 38 and Figure 39.

Figure 38 illustrates a fictional example of a neighbourhood with three streets and 23 houses, connected to a power station. The shown loads per street have been calculated by assuming that each house has an average maximum load that corresponds to the day that what was found in Table 7 for Almungebygden at 75% CEVs in houses; a load of 4,951 W excluding the CEV load (which occurred at 19:10 on a December in Tuesday). This gives the total load for Street A of 45 kW, 4,951 W x 9 houses. The same load was assumed for the other streets and houses. Figure 38 further shows that this particular neighbourhood’s load aggregates up to 115 kW during this particular time, day and month (19:10 on a December in Tuesday).
Table 7: Increase in max load (%) per household, for different CEV shares of cars in traffic for selected areas in Uppsala Municipality. Ho. = House, Apt. = Apartment

<table>
<thead>
<tr>
<th>Area</th>
<th>25%</th>
<th>75%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unweighted average</strong></td>
<td>5.4% 2.4%</td>
<td>18.4% 12.8%</td>
<td>22.3% 16.8%</td>
</tr>
<tr>
<td>Almungebygden</td>
<td>5.1% 2.2%</td>
<td>17.6% 11.7%</td>
<td>21.4% 15.7%</td>
</tr>
<tr>
<td>Berthåga</td>
<td>4.2% 1.9%</td>
<td>15.0% 9.3%</td>
<td>18.2% 12.3%</td>
</tr>
<tr>
<td>Björklingområdet</td>
<td>5.1% 2.2%</td>
<td>17.7% 11.8%</td>
<td>21.5% 15.8%</td>
</tr>
<tr>
<td>Danmarksbygden</td>
<td>4.9% 2.1%</td>
<td>17.1% 11.1%</td>
<td>20.7% 15.0%</td>
</tr>
<tr>
<td>Eriksberg</td>
<td>5.6% 2.4%</td>
<td>19.3% 13.5%</td>
<td>23.4% 17.9%</td>
</tr>
<tr>
<td>Flogsta-Ekeby</td>
<td>2.4% 1.2%</td>
<td>9.6% 5.2%</td>
<td>11.8% 6.8%</td>
</tr>
<tr>
<td>Funbo bygden</td>
<td>5.6% 2.4%</td>
<td>19.3% 13.5%</td>
<td>23.4% 17.8%</td>
</tr>
<tr>
<td>Fäl hagen</td>
<td>4.9% 2.1%</td>
<td>16.9% 10.9%</td>
<td>20.6% 14.8%</td>
</tr>
<tr>
<td>Gamla Uppsala-Nyby</td>
<td>6.0% 2.5%</td>
<td>20.3% 14.6%</td>
<td>24.6% 19.2%</td>
</tr>
<tr>
<td>Gamla Uppsala bygden</td>
<td>5.0% 2.1%</td>
<td>17.4% 11.4%</td>
<td>21.1% 15.4%</td>
</tr>
<tr>
<td>Gottsunda</td>
<td>7.0% 3.2%</td>
<td>23.5% 18.0%</td>
<td>28.4% 23.3%</td>
</tr>
<tr>
<td>Grünby</td>
<td>7.7% 3.7%</td>
<td>25.4% 20.0%</td>
<td>30.7% 25.8%</td>
</tr>
<tr>
<td>Häga</td>
<td>3.7% 1.7%</td>
<td>13.4% 8.1%</td>
<td>16.4% 10.4%</td>
</tr>
<tr>
<td>Innerstaden</td>
<td>3.8% 1.7%</td>
<td>13.8% 8.4%</td>
<td>16.8% 10.7%</td>
</tr>
<tr>
<td>Järlåsbygden</td>
<td>4.8% 2.0%</td>
<td>16.6% 10.6%</td>
<td>20.2% 14.4%</td>
</tr>
<tr>
<td>Knuthbygden</td>
<td>4.4% 1.9%</td>
<td>15.4% 9.6%</td>
<td>18.7% 12.9%</td>
</tr>
<tr>
<td>Kung sängen</td>
<td>9.8% 5.4%</td>
<td>31.9% 27.0%</td>
<td>38.7% 34.1%</td>
</tr>
</tbody>
</table>

According to Eachus-Jönebring (2017) and Johansson (2017), the power stations on this level in the distribution grid are, on average, dimensioned at approximately 70% of the maximum load. The maximum load was shown to be 6,193 W (which occurred at 18:10 on a Saturday in January) in Figure 32. Thus, the power station in this example would be expected to have a maximum capacity of 203 kW. This also means that on an average Tuesday in an average December at an average 19:10, the power station is running at 56.7% of its capacity, when there are no CEVs.

Figure 39 shows the same neighbourhood as in Figure 38 but with CEVs. According to the example it is assumed that CEVs make up 75% of all cars in traffic and that there is 1.33 cars per house (in Almungebygden). This would cause, as
Figure 38: Neighbourhood and power grid illustration without CEVs of 23 houses with a house load of 4,951 W each

shown in Table 7, an increase, relative the max load, of 15.7%. Thus, a household max load of 6,193 W \times 1.157 = 7,165 W or a total neighbourhood load of 164 kW which would be 81% of the power station’s capacity. Thus, the previous highest running rate, after which the power station was dimensioned, has increased from 70% to 81% which is an increase of 15.7%. This means that the power stations will, if you have aggregated enough houses under one power station, see an increase in their highest running rate corresponding to that which is presented in Table 7. A second important finding is that the previous max peak for the household load used to be at 18:10 on a Saturday in January but is now expected to occur at 19:10 on a Friday in December. Thirdly, the max load that day, Friday in December, increased from 115 kW to 164 kW which is an increase of 43%. Fourthly, these results are on top of the expected increase in household load projected by Liljeblad (2016), thus the total increase household load compared to the data in the database provided by the Swedish Energy Agency is even higher (by a factor of an additional 12.5%. See Table 5) Important to note is that if too few houses are connected to one power station the results are likely to vary so much that deviations of 100% of the expected value is not unthinkable.
6.4 Sensitivity Analysis

The findings presented in this section are built on a model that allows each contributing factor to be modified, both to allow different scenarios to be procured as well as to facilitate investigating which factors have a big and small impact on the end result.

Further is an investigation into how the following three factors affect the final result (increase in max load). This analysis has been done by looking at houses and apartments in Almungebygden separately.

- Distance driven per day on average (compared to the national average)
- Charging power (W)
- Number of households per power station

Table 8 shows how and increase or decrease in the average driving distance potentially increases the max load. The tables shows the relative increase or decrease to the results presented in Table 7 for Almungebygden. As the table shows, if the average distance driven is less in an area in Uppsala, the increase in max load is expected to be smaller, and vice versa. The table also shows that the impact of the factor driving distance does not always have a linear impact on the end result, but rather that it depends on the presumed relative (to the household load) impact
from the CEVs at 0% change from the average driving distance. If the presumed relative impact from the CEVs at the average driving distance is very high (at high CEV shares and for Appartments) then an increase in the average driving distance will have a small effect on the results. The opposite also applies, if the presumed relative impact is very small (at low CEV shares and for houses) then an increase in the average driving distance will have a big effect on the results. This explains why apartments would not experience as big of a difference as houses would if the actual average driving distance is larger in a particular area. This is because the CEV load is expected to have a bigger relative impact on the household loads in apartments rather than houses.

<table>
<thead>
<tr>
<th>Share of CEVs</th>
</tr>
</thead>
<tbody>
<tr>
<td>25% 75% 90%</td>
</tr>
<tr>
<td>- 50% -55% -52% -53% -48% -54%</td>
</tr>
<tr>
<td>-10% -11% -1% -1% -10% -1%</td>
</tr>
<tr>
<td>0% - - - - -</td>
</tr>
<tr>
<td>+10% 0% 20% 0% 20% 0% 11%</td>
</tr>
<tr>
<td>+100% 24% 129% 37% 67% 39% 53%</td>
</tr>
</tbody>
</table>

Table 8: Sensitivity analysis showing the effects on increase in max load by increasing or decreasing the driving distance. The results are relative what was presented in Table 7 for Almungebygden

Table 9 shows how an increase or decrease in the average charging power potentially increases the max load. The table shows the relative increase or decrease in the results presented in Table 7 for Almungebygden. As the table shows, if the average charging power is less in an area in Uppsala, the increase in max load is expected to be smaller, and vice versa. Further, the table shows that an increase in charging power is not likely to have a one to one effect on the results, but rather 10 or 5 to one, meaning an increase in the power by 100% to 500% will cause an effect of around 20% to 100%. The analysis also indicates that areas with houses are more 'vulnerable' to increase in charging power. This is probably to due to the fact that houses have more cars on average than apartments do. For example in Al-
mungebygden there are 1.33 cars per house and 0.35 cars per apartments, meaning there are 3.8 more cars in houses than in apartments in Almungebygden.

An interesting data point in Table 9 is the '-11%' in apartments, at 25% CEVs and a charging power of 7.36 kW. Here, an increase in charging power is expected to cause a smaller increase in max load than if the charging power was 3.68 kW. This is likely explained by the few number of CEVs, due to the few number of cars in apartments and the low share of CEVs. It means that at this charging rate, the overlap from multiple CEVs charging at the same time is smaller (because the CEVs finish charging quicker) and thus lowering the overall max load. However, as the table also shows, this is only applicable at 25% CEVs and in apartments.

<table>
<thead>
<tr>
<th>Charging power ∆ (kW)</th>
<th>25%</th>
<th>75%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>-38% (2.30)</td>
<td>-36%</td>
<td>22%</td>
<td>-25%</td>
</tr>
<tr>
<td>0% (3.68)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>+100% (7.36)</td>
<td>-11%</td>
<td>53%</td>
<td>22%</td>
</tr>
<tr>
<td>+200% (11.04)</td>
<td>17%</td>
<td>60%</td>
<td>55%</td>
</tr>
<tr>
<td>+500% (22.08)</td>
<td>45%</td>
<td>76%</td>
<td>57%</td>
</tr>
</tbody>
</table>

Table 9: Sensitivity analysis showing the effects on increase in max load by increasing or decreasing the driving distance. The results are relative what was presented in Table 7 for Almungebygden

Lastly, to investigate the effect of number of households per power station, i.e. if new houses are being built, Figure 40 illustrates an example. Given that power stations are dimensioned according to 70% of the expected max load in a neighbourhood, Figure 40 aims to investigate and illustrate the effects if the number of households per an existing power station was to increase. Figure 40 is based on the same example as in Figure 39 but with another house built (4% increase compared to the 23 houses in the figure).

Figure 40 shows that the total load would increase from 115 kW, as shown in Figure 38, to 171 kW. This would correspond to a running rate of 84% of the power station’s capacity. The increase from 115 kW to 171 kW on that day, that month
and that time is due to both the added house as well as the expected CEV load. The added house would increase the max load from 70% of the capacity to 73% (increase by 4%). Further the CEV load would increase the max load by the same 15.7% as described previously. Thus, $73\% \times 1.157 = 84\%$. This means that if more houses are added to existing power stations the effect will be the product of the increase in number of houses multiplied by the expected increase in max load due to CEVs per house.

![Figure 40: Neighbourhood and power grid illustration with CEVs of 23 + 1 houses with a house load (incl. a CEV load) of 7,165 W each](image)

Figure 40: Neighbourhood and power grid illustration with CEVs of 23 + 1 houses with a house load (incl. a CEV load) of 7,165 W each
7 Results

This section presents the results that answer the two SQs that in turn help answer the MRQ.

7.1 SQ 1 - How many CEVs and of what kind will there be in Uppsala and in relevant nearby areas in 2030?

Section 4 presents the findings on what the development of CEVs will look like in Uppsala 2030.

In Figure 20 it is shown that there will be roughly 71,000 CEVs on the road by 2030, according to the projections. This corresponds to a vehicle fleet share of 73% of the total number of cars (that is projected to be roughly 96,000).

Regarding the development of CEV models, Figure 17 indicates that 1) All major car manufacturers have already made or are planning on a CEV debut and 2) The car models will, within nearby releases, have an EPA range of 300+ km and likely to continue improving well into the 2020’s. The range improvements are likely to continue to soon reach the same range capacities as those in traditional ICEs today. The research behind Section 4 also indicates that the sub-category to CEVs, BEVs, will be the most prominent CEV type as the PHEV is considered a ’transition’ vehicle to fully adopting BEVs.

The findings regarding charging infrastructure suggest that home charging will be the most common CEV charging behaviour. This is due to the fact that the lower power charging options, that are available at a low or no cost, will suffice for the average daily driven distance.

7.2 SQ 2 - How will CEVs impact the distribution grid in Uppsala in 2030?

As presented in Section 6, the expected impact on the distribution grid due to charging by CEVs is measured by simulating the CEV load and comparing its size to the current household loads.
Firstly, the findings show that the household load in apartments is much lower than in houses (as seen in Figure 32), and that the overall household load is much lower in the summer than it is in the winter (as seen in Figure 30 and Figure 31).

Secondly, the findings show how the driving patterns, presented in Section 5, translate into a load that is comparable to the household load of both houses and apartments. The findings show that the highest load due to CEVs is not expected to succeed 1,400 W per car (as shown in Figure 35). This means that less than half of the cars in a sample are expected to charge at the same time when the peak is the highest. This is assuming a charging rate of 3.7 kW and that the sample size is sufficiently large.

Thirdly, once the household loads and the CEV loads were compared to each other the findings show that the CEV load can, during a certain times of the day, certain days of the week and certain months of year, cause an increase to the max load expected in the distribution grid. This is shown in Figure 36 and in Figure 37.

Lastly, the findings summarize the above three points, by extracting and searching for biggest increase in max load expected throughout day, day of the week and month of the year. This is presented in Table 7. The findings, presented in Table 7, are illustrated with an example in Figure 38 and Figure 39. This final finding showed that the expected increase in max load varies with the different areas in Uppsala as well as with different CEV share of cars in traffic scenarios. The figures helped illustrate that the increase in max load per household will have a direct impact on the power stations capacity.

Further, a sensitivity analysis was conducted that showed the following three things.

- The change in average driving distance in an area has an impact on the increase in max load depending on the CEVs overall relative impact on the household load
- The change in average charging power in an area has impact on the increase in max load that is proportional to the increase or decrease in charging power, but the impact is smaller than one to one
• If more houses were build in an area, the impact due to CEVs would be even greater, by a factor proportional to the increase in number of houses

Overall the results have led to the following conclusions regarding what effect CEVs will have on the distribution grid in Uppsala 2030.

• CEVs are expected to have a significant impact on the household load and therefore, by extension, on the distribution grid and its power stations
• CEVs will have a bigger relative impact on the household load in households where the energy consumption is small such as as apartments but also, by extension, households with direct heating
• CEVs will have a bigger impact on the household load in areas where the number of cars per household is high
• The higher the CEV load is, the smaller the difference will be in impact on houses compared to apartments. Also, the higher the CEV load is, the closer the ‘worst peak load day’ gets to the day of the worst CEV load as the CEV load will be the more determinant factor in the household load

7.3 MRQ - Which measures should Vattenfall take in order to sustainably react to the expected increase in CEVs in Uppsala by 2030?

Given the findings presented in Section 7.1 and 7.2 that are supported by Section 4 to Section 6, the following measures should be taken by Vattenfall in order to sustainably react to the expected increase in CEVs in Uppsala by 2030.

Monitor specific areas with a high concentration of cars, low energy consumption per household and that already have substations with a capacity that is below the typical dimensions. These are factors that have big impact on how CEVs will affect the grid and therefore these are the areas that are most likely to first encounter problems when CEV sales start to increase.

Follow CEV sales to reevaluate the projections made in this study. By doing this Vattenfall will know if the development is moving faster or slower then projected and can plan actions accordingly. This should be done by subscribing to
Trafas publications that are published every month. It can also be done together with e.g. Power Circle, to develop a tool that monitors the development at a detailed geographic level. This would allow for Vattenfall to monitor CEV development on a more detailed geographical level than what has been done in this study.

**Monitor trends of car ownership** to be able to evaluate if it will affect people’s CEV charging behaviour and render the model completely incorrect. These trends include for example joint car ownership (carpools or otherwise) and autonomous vehicles that if widely adopted would change people’s charging behaviour dramatically. This would make the prediction of how CEVs will impact the distribution grid wrong, drastically affecting the results in this study.

**Review Velander constants** to make grid planning take the load due to CEVs into consideration (This is explained further in Section 9.2.3). This should be done by looking at transport data and travel patterns to incorporate how, when and where people travel as a part of how they use electricity. Given the current situation and the expected increase in CEVs, it is believed that transportation in general will have a significant impact on how electricity is consumed in the future. When reconstructing Velander constants it is important to understand that the findings in this study are applicable when looking at a specific level in the distribution grid. When taking actions based on these findings there is a need to understand that at lower levels in the grid, with samples of only a few households, there will be bigger variations in the impact and actions must be adjusted accordingly. The opposite also applies, namely that at regional level, the effects of the CEV load are not expected to be at all significant.

**Investigate smart charging** as a possible solution, to shift the CEV load peak to a different time of day (presumably during night). The recommendation is to adopt a simple use of smart charging where the starting time of charging is moved a couple of hours to 'shave' the worst peak. This could be done by providing a technical solution to supplement the existing charging solutions that only ask when you want to use the car in the morning and then adjusts the charging
to start as late as possible given this information and the SOC of the battery. The value of this would be highly motivated by the alternative cost of upgrading infrastructure due to an increase max load.
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8 Discussion

This section consists of a discussion of the impacts and reliability of the various results that our model has provided. The section also discusses the recommendations that we give and what scenarios that might impact the recommendations. Furthermore the section also discusses some of the assumptions we have made when creating our model and what implications these assumptions have had on the final results.

8.1 Discussion of our Results

This subsection discusses the results presented in Section 7. The results are reviewed as to whether or not they are likely and reasonable.

8.1.1 SQ 1

Our estimation of 71,000 CEVs in Uppsala by 2030 is based on roughly 4 million CEVs in Sweden by the same year. This number may seem high, considering the low share of CEVs today and that Power Circle project only 1 million CEVs on the road by 2030. However, as pointed out throughout this report, projections stretching far into the future (5+ years) are extremely hard get right.

If we look at the projections for CEVs both in Sweden and Uppsala (Figure 18 and Figure 20), there is a notable acceleration in the market share after the year 2022. This is due to the projected price parity that Randall (2016) predicts that in turn implies that there will be few or no incentives not to by a CEV instead of an ICE.

When comparing the projected and historical CEV sales in Sweden with the CEV sales in Norway seen in Figure 10, it is notable that currently Sweden is 'lagging' behind Norway by 3-4 years. When comparing the projections presented in Figure 19, this 'lag' would be 7 years in 2021 compared to Norway. This suggests, if assuming all else equal, that these projections are modest and underestimating until the year of 2021. The same argument applies when comparing Sweden to the CEV market share in the Netherlands as shown in Figure 4. After 2021, assumptions of price parity have been applied and thus these types of historic comparisons
are unreasonable, as the growth is expected to be far from linear.

An interesting point of discussion, is the implication of the 'tipping point’ in CEV sales happening sooner or later than what we have projected and what the implications would be to our results. We have predicted this 'tipping point’ to happen 2022, when Randall (2016) predicts price parity to be reached. What would the implications be if this happens later (or sooner) than when we have assumed? The answer to this is quite simple, assuming that CEVs will be the dominant vehicle type at one point in time. If that can be assumed, the implication of when this 'tipping point’ will occur will simply shift the year when 100% of new vehicles will be CEVs. Once that has occurred, it is reasonably a matter of enduring the average scrapping time (14 years in Sweden) until the entire fleet of personal vehicles will have shifted to CEVs.

From 2016 to 2030 it is projected that the number of new cars that will be sold will increase from 388,000 to 520,000. That means that for every year that the boom is 'off’ from our projections, the total stock of CEVs in Sweden will be roughly 430,000 cars greater or smaller. If, for example, the boom is delayed by 2 years to 2024 there will be almost 1 million CEVs less in Sweden by 2030 (and 15,000 CEVs less in Uppsala). This highlights the importance of identifying when the 'tipping point’ will be reached.

There are several factors that could contribute to reaching the 'tipping point’ in the near future. There is the introduction of the Bonus-Malus system as discussed in Section 3.1.1 that could fuel the shift to CEVs. There is the development of new models that are becoming more and more price competitive as well as the development of the necessary infrastructure.

We believe that the projections made by Power Circle (2016a) are very modest, primarily because their projections show that the most explosive shift in the CEV market has already occurred and that they project that the acceleration is decreasing. To be noted is that our projections are in line with what Power Circle (2016a) have projected until 2021, however after we assume price parity our projections diverge.
An example, illustrating the difficulty in predicting the future, especially when it comes to technical development, is the case with the Swedish company Facit. Facit was a manufacturer of mechanical typewriters and calculators with 14,000 employees worldwide and a revenue of over 1 billion SEK in 1970. But in 1972 the company was facing bankruptcy due to electronic appliances taking over the market completely when Facit, at the same time, refused to adapt their products to the new standard. In November 1972 Facit was sold to Electrolux for only 80 million SEK. Thus, over the course of two years one way of creating a product was completely outdated. (Petersson 2004)

Another example is how industry experts such as Gartner, McKinsey & Co, Foresters, etc were consistently failed to predict the growth of the mobile industry (Ismail 2015). Figure 41 shows how these industry experts constantly, even after several attempts, kept underestimating the future exponential growth of the mobile industry.

![Figure 41: Mobile Industry projections, where the coloured lines show projections (CAGR) made by industry experts and the black line the actual progression (Ismail 2015)](image-url)
In summary it can be said that these type of projections are hard to get right. However, for our intents and purposes the exact number of CEVs in Sweden and in Uppsala 2030 is not crucial to the results of this study. The overall take-away is that the sales of CEVs is likely to continue increasing and that an eventual 'tipping point' is likely to occur before 2030.

8.1.2 SQ 2

Our findings from Section 5 and Section 6 is what lays the foundation for our results and answering of SQ 2.

Our findings regarding driving patterns are generated from the TSS database. The overall findings on driving distance per day can be compared with the national statistics from Trafa, to verify the quality of the database. According to Trafa, the driving distance per day in Västra Götaland was 34.3 km in 2012. When we compiled the data points we calculate these figures to be 32.4 km per day, consisting of data between 2010-2012, indicating that the data is reliable. This is important since we rely on the driving pattern data when we estimate the needed charging power and by comparing it to national statistics we get a confirmation that the data seems correct.

The assumptions that we have made to be able to conduct the analysis of the driving pattern data is described in Section 5 and some are discussed later in this section. The assumption that affects the result on SQ 2 in the biggest way is that we assume that driving patterns found by analysing measurements of ICEs in the TSS database will be transferable to driving patterns of CEVs in 2030. Since CEVs of today have a shorter driving range than ICEs it is reasonable to think that CEVs will drive shorter distances. However, since we want to look at the impact from CEVs in 2030, and since the development of CEVs point to rapid increase in range, we believe that these differences can be neglected for 2030. Also, to look at the driving patterns of CEVs today would incorrectly depict how the average CEV driver in 2030 would drive. This is because the owners of CEVs today are considered 'early adopters' and thus would not be a fair representation of 2030 when CEVs are likely to be the standard. We believe that a more correct estimate of CEVs driving
patterns in 2030 is obtained by looking at the standard today, which is why we look at how ICEs drive today.

Regarding the generic finding on household electricity usage, there is no need for discussion as they are 1) only used as a point of reference in this study and 2) widely discussed in other forums.

However, the fact that the CEV load curves seem to closely follow the household load curves is more interesting. This is somewhat expected as the electricity load in households is driven by people being at home which coincides with people’s driving habits. The fact that the household load peaks at 18:00 - 19:00 is most likely explained by people returning home from work or school at that time which gives the load from CEVs a similar ‘shape’ to that of the household load. Since our model is focused on the last stop of the day and that charging starts at that point it gives the curve a shape that translates to when people arrive at home. We have, throughout the length of the report, stated that we have chosen this method to simulate a ‘worst case’ scenario of the impact on the grid from CEVs’ charging, and since we believe that this charging pattern will be dominant in 2030 (more on this in Section 8.2.3).

The result that the highest load due to CEVs charging is not expected to be above 1,400 W per car is also noteworthy as the model has assumed 3.7 kW as charging power. This means that, on average, for a larger sample, there is less than half of all cars charging at the same time (at max peak) even if all cars would be CEVs. This result is key, as it explicitly translates into how grids in the future can and should be dimensioned by taking the CEV load into consideration. This type of statistical indication of how to dimension a grid, according to how electricity is consumed, is exactly the same as how Velander constants are used in current grid dimensioning methodologies Eachus-Jönebring (2017).

Our final result of the different areas in Uppsala Municipality and the increase in max load given different CEV share of cars in traffic, gives a more detailed view of how CEVs will affect the grid. The results indicate that there are differences in the impact on the grid depending on the types of households and number of vehicles.
per household. The results also show that there are differences in the impact on the grid between apartments and houses.

Our results, in terms of increase of the max peak load, range from 2% to 39% depending on CEV share, household type and area. These numbers are in the same order of magnitude as the projected increase in household electricity usage, provided by IVA. IVA predicts a 12.5% increase in max load by 2030. We can also look at the study conducted in the United Kingdom by Qian et al. (2011), where the author finds that at only 20% CEV share, the daily increase of electricity usage can be 36%, in a 'worst case' scenario. This study is conducted with a different methodology and was made in 2011. In the same way as by comparing with IVAs figures of future electricity usage, the figures point in the same direction and in the same order of magnitude as our results.

Further we have showed how these results would impact a single power station by aggregating the households’ loads into one junction. As shown in Section 6, the effects on the power stations are in direct proportion to the effects per each household, which is discussed above. This type of example case gives a good and real indication of how our result will directly impact the grid.

8.1.3 MRQ

The final recommendations that we give Vattenfall answers our MRQ and is presented in Section 7.3. The rationale and motivation behind our recommendations are based on our results presented to answer SQ 1 and SQ 2. In terms of how reasonable our recommendations are, we believe that given that the sales and development of CEVs is expected to 'boom' (SQ 1) and that the load due to CEVs is expected to have a significant impact on the distribution grid (SQ 2), it is justifiable to attribute a high focus to take action on this matter. We believe that Vattenfall should do this in accordance with our recommendations. We support this by our case example over Uppsala Municipality 2030, however the recommendations can and should be applied in a more general sense.
8.2 Discussion of our Assumptions

Throughout the time of our research we have made several assumptions and simplifications in order to create a working model and to be able to generate results. In this subsection the implications on the results of the most drastic assumptions and simplifications are discussed.

8.2.1 CEV projections 2030

There are mainly two assumptions when making the projections on the number of CEVs that need to be discussed further. Other assumptions are accounted for in Section 4.

The first assumption is that we have chosen not to take scrapping of CEVs into account. This assumption has been made because 1) the average life cycle of a car in Sweden is 14 years, (thus, a significant number CEVs will not start being scrapped until the late 2030’s) and 2) CEVs are assumed to have a longer life span (due to the possibility of changing the battery and not the entire car). Thus, this gives an aggregated number of CEVs that consist of all CEVs sold in Sweden from now until 2030. This suggests that the ‘actual’ number of CEVs 2030 might be slightly smaller.

We also assume that there will not be a change in buying behaviour when the predicted ‘tipping point’ of CEV sales has been reached. By this we mean that the number of new cars sold per year will continue according to historical sales figures. However, it is not unreasonable that a dramatic shift to CEVs, and therefore significant advantages in price and maintenance, will cause an even more dramatic shift to CEVs than the previously linear historical sales data may indicate. Or to put it differently, if CEVs become attractive enough for consumers, they may consider buying a new car before they need to, making the transition to CEVs in Sweden even faster than what we have predicted.

The discussion of these two assumptions point in two different directions. Overall, our belief is that our projections are optimistic but that there is still room for the final number of CEVs 2030 to be even higher than what we suggest. The as-
sumption that have larger effects on our projections is the effects when price parity is in place, which is discussed in Section 8.1.

8.2.2 Analysis of Driving Patterns 2030

When producing the driving patterns model, there are two assumptions that need to be addressed in more detail.

The first assumption is that each registered vehicle is treated in an aggregate form. This means that all data points for all cars have been summed up. This is logical since we are not interested in distinguishing different cars or drivers from each other, but are rather interested in a statistical average. In doing this there is a risk of certain vehicles and drivers being overrepresented in the statistical average. However, as the average driving distance of the aggregated data is close to that of Trafa’s presented figures, the aggregation seems fair. We recognize that this is not conclusive evidence.

The second assumption is that the data that has been processed has been processed assuming that a ‘driving day’ starts at 00:00 and ends at 23:59 with not overlap allowed. This creates a possible error if the ‘last stop of the day’ is in fact after 23:59 (someone arriving home after midnight). In this case our model will register the second to last stop of the day as being the last stop. The model will then compile the distance driven up until that stop and disclose that the amount of kWh that needs to be charged will correspond to that distance. The actual last stop (maybe at 00:25) is instead registered to the next day. This means that the total distance driven (and thus the connected power needed to be charged) will not be wrong but the charging starting time may be shifted. However, according to the raw data, this possible ‘mistake’ happens less than 0.5% of the registered days, thus having a very small impact overall which makes it reasonable for us to discard.

8.2.3 CEVs’ impact on the Uppsala grid 2030

When analyzing the data of grid impact there are two assumptions that we have made that need to be addressed in more detail.

The first assumption is that charging of CEVs is done at the last stop of the
day and that this stop is at home. We made this assumption since evidence point to home charging being the most common way to charge and that it is reasonable to assume that a driver is at home when the driver stops for the last time. This assumption is also verified by Heesterman (2017), Associated Manager at Home Charging Installations at Tesla Motors. This assumption made the large number of data points much more manageable. There is one major possible flaw in this assumption. If people charge a lot of the needed power on locations that is not at home (the office, stores, etc.), our model will be skewed, showing a larger charging need than what would be realistic. Since we want to have a ‘worst case’ approach on the implications and since most drivers will cope with only charging at home, we have chosen to discard this possibility.

The second assumption is that CEVs are always charged until they have a ‘full tank’. Regardless if this assumption is unrealistic or not, it doesn’t matter. As the data behind the model is aggregated to always show a 24h period and encloses data from the entire year, the charging need per day will correspond to the average distance travelled that day. Thus, on a daily basis where each sequential day is similar, this assumption is fair. However, in cases such as Friday night to Saturday morning or Sunday night to Monday morning, this might cause a bigger problem as those sequential days have been shown to vary a lot more than say Tuesday to Wednesday. This is not believed to be a huge source of error but is yet recognized as a possible one.

8.3 Externalities unaccounted for

This subsection discusses several scenarios that have intentionally not been taken into account in this study but could completely change the way our MRQ is answered.

8.3.1 Car ownership 2030

One of the big questions that arise when evaluating the results and implications presented in this report is what the future of car ownership will look like.
In our research we have assumed that there will be a continued increase in number of vehicles in Sweden, following the development of the past 10 years. This is reasonable since there are today no signs of car ownership changing. Both number of new cars per year and the total number of cars are increasing and we have assumed that this development will continue to 2030. However, there are several factors that might change that.

One example is joint car ownership and carpools. BMW’s Drive Now and Volvo’s Sun Fleet are current examples of this. This type of car ownership means that there is more than one household that own the car that the household uses which will result in fewer cars per household and fewer cars in total. There is today a relatively small number of households that have adopted this type of car ownership and those that have often use it as a ‘secondary car’, owning the firs car in a conventional way. However, with new business models and changed needs in car usage, this might change.

If carpools and joint ownership was to increase the impact on our findings will be mostly regarding number of cars per household, which we have seen have a big impact on the load from CEVs charging. Fewer cars per household will mean fewer cars charging at peak time and thus a smaller impact on the max load.

Another factor related to how we will use cars in 2030 is the concept of ‘peak car’. Peak car refers to the time when we start using the car less and less and driving shorter distances than before. The biggest driver is expected to be urbanisation, i.e. people moving into cities and not needing a car to get around.

We have assumed that driving patterns will not change from today to 2030 and that CEVs will be driven the same way as ICEs are driven today. If ‘peak car’ was to happen it would mean that the usage of cars would drop and thus resulting in fewer and shorter trips.

If this is the case, the parameter that will impact our findings that is going to change is driven distance. If fewer and shorter trips are made (but the total number of cars still increases), the needed charging distance per car is going to be lower. This will affect the maximum load peak, however, less compared to if number of
In our model we have looked at the household electricity usage today and, by using projections of future electricity usage made by IVA, adjusted the load curves to be accurate for 2030. These projections, like with the ones we make on CEV development, are hard to get right but since IVA have broken down the usage in
detailed level there is no reason for us to question it or make other projections.

Factors that might change these projections and especially change the peak load could be adoption to battery usage in households. This would mean using batteries (maybe from old CEVs) to 'peak shave' usage during peak hours. This could lead to a more even usage of electricity, where electricity usage would increase during the night and the middle of the day by charging the batteries and decrease during peak hours by discharging the batteries.

This would give the same overall household electricity usage as in our model but a lower max peak usage, giving the impact from CEVs charging a higher percentage change. However, since the electric grid is already dimensioned for the usage today (or the usage when the grid was built), a lowered max peak usage will make the impact on the grid from CEVs charging smaller.

### 8.3.4 Summary externalities

Table 10 presents a summary of the unaccounted externalities. They are ranked in likelihood of happening and affect on MRQ and ranked from low to high.

<table>
<thead>
<tr>
<th>Externality</th>
<th>Likelihood of happening</th>
<th>Affect on MRQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car ownership changes</td>
<td><strong>Medium:</strong> All figures point to car ownership continuing to increase thus this is deemed not likely. However, predicting the future more than 10 years ahead is proven hard</td>
<td><strong>High:</strong> A dramatic decrease in number of cars per household will affect the results in a significant way. Making the impact from CEVs charging on the grid smaller</td>
</tr>
<tr>
<td>Peak car hits</td>
<td><strong>Low:</strong> It is unlikely that the distance driven per car is to decrease (which is the definition of peak car)</td>
<td><strong>Medium:</strong> The distance driven has a relatively small effect on our results</td>
</tr>
</tbody>
</table>
Autonomous cars take over

**Low:** It is deemed unlikely that self driven cars will have a big penetration by 2030. They will probably exist (they already do exist today) but the belief is that due to regulations they will not have replaced regular driven cars by 2030.

**High:** The impact on our model if autonomous cars take over will be large. This is because both the number of cars and driving patterns would change drastically.

CEVs are outperformed by other technology

**Low:** It is deemed highly unlikely that other technology will surpass CEVs. Investment by all the major car manufacturers is in CEV model development.

**High:** If, e.g. fuel cell cars would replace CEVs our entire model is irrelevant since charging cars would not be needed at all.

Electricity usage change

**Low:** The projections made by IVA is deemed as reliable.

**High:** If the change means lowered max peak the affect on our model will be high since we look at how CEVs affect the max peak in households.

<table>
<thead>
<tr>
<th>Externalities</th>
<th>Low: Description</th>
<th>High: Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autonomous cars take over</td>
<td>It is deemed unlikely that self driven cars will have a big penetration by 2030. They will probably exist (they already do exist today) but the belief is that due to regulations they will not have replaced regular driven cars by 2030.</td>
<td>The impact on our model if autonomous cars take over will be large. This is because both the number of cars and driving patterns would change drastically.</td>
</tr>
<tr>
<td>CEVs are outperformed by other technology</td>
<td>It is deemed highly unlikely that other technology will surpass CEVs. Investment by all the major car manufacturers is in CEV model development.</td>
<td>If, e.g. fuel cell cars would replace CEVs our entire model is irrelevant since charging cars would not be needed at all.</td>
</tr>
<tr>
<td>Electricity usage change</td>
<td>The projections made by IVA is deemed as reliable.</td>
<td>If the change means lowered max peak the affect on our model will be high since we look at how CEVs affect the max peak in households.</td>
</tr>
</tbody>
</table>

Table 10: Different externalities’ risk and affect on our MRQ

Looking at Table 10, we see that all but one of the investigated externalities have a low chance of happening, making it reasonable not to include them in our model at this stage. We can also see that factors that implicate number of cars per household have a higher impact on our results and that there are externalities that, if they occur, make our model completely irrelevant. Overall it should be stated that if changes are to happen by 2030 it is probably in the area of how we will own and use cars overall. Looking to the future, it points to fewer cars in total and that the driving distance per car will increase.
9 Conclusion

This section presents the conclusion of this thesis. It also answers the research question with the final recommendations as well as leaves suggestions of improvement for future work.

9.1 MRQ

We believe that given that the sales and development of CEVs is expected to ‘boom’ (SQ 1) and that the load due to CEVs is expected to have a significant impact on the distribution grid (SQ 2), it is justifiable to attribute a high focus to take action on this matter. We believed that Vattenfall should do this in accordance with the recommendations in this report. We support this by our case example over Uppsala Municipality 2030, however the recommendations can and should be applied in a more general sense.

• Monitor specific areas with a high concentration of cars, low energy consumption per household and that already have substations with a capacity that is below the typical dimensions
• Follow CEV sales to reevaluate the projections
• Monitor trends of car ownership to be able to evaluate if it will affect people’s CEV charging behaviour and drastically affect the results in this study
• Reconstruct Velander constants to make grid planning take the CEV load into consideration
• Investigate smart charging as a possible solution, to shift the CEV load peak to a different time of day

9.2 Future Work

This subsection presents the proposed changes and follow ups that future work in this area should include. This comprises of both improvements to the work in this study as well as perpetuating work that could be done.
9.2.1 CEV projections

The CEV projections made in this study are, as stated previously, used as a point of reference to be able to generate relevant results from the model. As previously stated, Power Circle (2016b) predict 25% market share of cars in traffic by 2030, this study predict 75%. As car manufactures release their responses to the predicted CEV ‘boom’ in the upcoming 2-3 years, these projections can likely be made a lot more accurate. This would help ‘zero in’ which of the scenarios, 25%, 75% or 90% (or a completely different one) market share of cars in traffic by 2030 is the most relevant.

9.2.2 Improved model

There are several areas where assumptions and simplifications have been made in the model used in this thesis. These are all described in detail in Sections 4 to Section 6. All of these could be improved by more detailed and reliable data sets. For example, all data used has been adjusted to fit Uppsala and the year 2030, the supporting evidence for those assumptions could be improved as more data is produced and made available. As discussed in Section 8, the fact that it is assumed that CEVs will drive the same way as ICEs and that CEVs will charge the way that have been assumed, has a big impact on the outcome of the model. Thus, a suggestion for future work would be to build a model based on actual charging behaviours, rather than assumptions based on driving patterns. However, this has to be done under the premises that the charging behaviours reflect how the average CEV owner will charge in 2030 and not how the early adopter CEV owner will charge. This is why the presently available charging behaviour data have not been used, as stated in Section 6.1, because it would assume that all CEV owners will charge like the early adopters in 2030.

9.2.3 Velander constants

Velander constants are used to statistically help dimension distribution grids. The constants are tailored based on different customer behaviours, i.e. electricity con-
sumption habits. These constants take things such as geographical location, electric or district heating and size of household into account to be able to statistically ensure that the load in the grid will not surpass a certain desired percentage (Haglund & Johansson 2002). Thus, the suggested future work would be to procure new Velander constants that take the CEV load into consideration.

9.2.4 Business opportunity in grid impact

The desire from the beginning of the research was to be able to investigate the economical opportunities for Vattenfall in knowing the impact on the grid from CEVs charging.

Since specific information, on both the exact specification on the grid in Uppsala (capacity and load) as well as the financial implications of changing / rebuilding the grid, were unsuccessfully gathered, the possible economical costs from knowing the impact on the grid could not be calculated.

For future work it is therefore suggested that Vattenfall investigate what the implication are of our findings. This should be done 1) to better predict the needed grid investments and 2) to better understand what services and products are needed, both to benefit the consumers (CEV owners) as well as Vattenfall (by for example shifting the load to even out the max peak).
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A  Appendix - Interview take-aways

A.1  CEV Charging

Johan Tollin, Vattenfall & Rombout Heesterman, Tesla

- When charging at high effects, the SOC of the battery has an affect on the supplied power
  - High effects is generally viewed as over 20 kW
- When charging at low effects the supplied power can be assumed as constant
  - Low effects is everything below 10 kW
- The majority of customers start charging when they arrive home
- A majority of customers charge at a rate below 11 kW when at home

A.2  Driving Patterns

Maria Börjesson, CTR

- Drive patterns varies with the seasons
- Seasonal variations can be modeled from congestion charge fees

A.3  Grid Infrastructure

Jonas Persson and Martin Johansson, Vattenfall & Per-Arne Eachus
Jönebring, Sweco

- Average house load is between 2-3 kW
- Velander constants are used when dimensioning the grid in different areas.
  - Velander constants need to be updated when CEVs are a factor in the household electricity usage
- Rural areas are fed from substations of approximately 200 kVA
  - Approximately 20-30 households per substation
• Urban areas are fed from substations of approximately 800 kVA
  – Approximately 100 households per substation

• The distribution grid is generally dimensioned at 70% of the expected max load

• A new substation costs approximately SEK 400,000

• Cables cost somewhere between SEK 200-700 per meter

• Cost of digging in preparation for new/expanded grid is approximately SEK 1000 per meter
B Appendix - Projections

<table>
<thead>
<tr>
<th>Year</th>
<th># CEVs in traffic</th>
<th># New CEVs</th>
<th># New Cars</th>
<th># Cars in traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td></td>
<td>276,344</td>
<td>4,278,995</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td></td>
<td>308,734</td>
<td>4,335,182</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>1,254</td>
<td>301,335</td>
<td>4,447,165</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>7,094</td>
<td>4,447</td>
<td>324,037</td>
<td>4,585,519</td>
</tr>
<tr>
<td>2016</td>
<td>26,824</td>
<td>12,283</td>
<td>388,014</td>
<td>4,768,060</td>
</tr>
<tr>
<td>2018</td>
<td>73,229</td>
<td>26,229</td>
<td>404,840</td>
<td>4,890,005</td>
</tr>
<tr>
<td>2020</td>
<td>301,335</td>
<td>4,447</td>
<td>324,037</td>
<td>4,585,519</td>
</tr>
<tr>
<td>2022</td>
<td>385,562</td>
<td>44,327</td>
<td>422,395</td>
<td>5,015,068</td>
</tr>
<tr>
<td>2024</td>
<td>1,205,516</td>
<td>176,284</td>
<td>440,711</td>
<td>5,143,330</td>
</tr>
<tr>
<td>2026</td>
<td>2,154,963</td>
<td>479,761</td>
<td>479,761</td>
<td>5,409,779</td>
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<tr>
<td>2028</td>
<td>3,145,582</td>
<td>500,565</td>
<td>500,565</td>
<td>5,548,136</td>
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<tr>
<td>2030</td>
<td>4,179,157</td>
<td>522,272</td>
<td>522,272</td>
<td>5,690,031</td>
</tr>
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</table>

Table 11: Our projections of the CEV development in Sweden, based on historic figures from Myhr (2016a) and own assumptions described in Section 4. Table 1 of 2

<table>
<thead>
<tr>
<th>Year</th>
<th>% CEVs of cars in traffic</th>
<th>% CEVs of new cars</th>
<th>% Non-CEVs of new cars</th>
<th>% Increase in new CEVs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>0%</td>
<td>1%</td>
<td>99%</td>
<td>219%</td>
</tr>
<tr>
<td>2016</td>
<td>1%</td>
<td>3%</td>
<td>97%</td>
<td>65%</td>
</tr>
<tr>
<td>2018</td>
<td>1%</td>
<td>6%</td>
<td>94%</td>
<td>30%</td>
</tr>
<tr>
<td>2020</td>
<td>3%</td>
<td>10%</td>
<td>90%</td>
<td>30%</td>
</tr>
<tr>
<td>2022</td>
<td>7%</td>
<td>40%</td>
<td>60%</td>
<td></td>
</tr>
<tr>
<td>2024</td>
<td>23%</td>
<td>100%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>2026</td>
<td>40%</td>
<td>100%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>2028</td>
<td>57%</td>
<td>100%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td>73%</td>
<td>100%</td>
<td>0%</td>
<td></td>
</tr>
</tbody>
</table>

Table 12: Our projections of the CEV development in Sweden, based on historic figures from Myhr (2016a) and own assumptions described in Section 4. Table 2 of 2
<table>
<thead>
<tr>
<th>Year</th>
<th># CEVs in traffic</th>
<th># New CEVs</th>
<th># New Cars</th>
<th># Cars in traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>129</td>
<td>134</td>
<td>7,333</td>
<td>79,540</td>
</tr>
<tr>
<td>2016</td>
<td>465</td>
<td>225</td>
<td>7,407</td>
<td>83,147</td>
</tr>
<tr>
<td>2018</td>
<td>1,262</td>
<td>452</td>
<td>6,978</td>
<td>84,287</td>
</tr>
<tr>
<td>2020</td>
<td>2,609</td>
<td>763</td>
<td>7,267</td>
<td>86,282</td>
</tr>
<tr>
<td>2022</td>
<td>6,621</td>
<td>3,027</td>
<td>7,568</td>
<td>88,325</td>
</tr>
<tr>
<td>2024</td>
<td>20,664</td>
<td>7,882</td>
<td>7,882</td>
<td>90,416</td>
</tr>
<tr>
<td>2026</td>
<td>36,869</td>
<td>8,208</td>
<td>8,208</td>
<td>92,556</td>
</tr>
<tr>
<td>2028</td>
<td>53,718</td>
<td>8,548</td>
<td>8,548</td>
<td>94,747</td>
</tr>
<tr>
<td>2030</td>
<td>71,236</td>
<td>8,902</td>
<td>8,902</td>
<td>96,990</td>
</tr>
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</table>

Table 13: Our projections of the CEV development in Uppsala Municipality, based on historic figures from Myhr (2016a) and own assumptions described in Section 4. Figures before 2013 were not acquired. Table 1 of 2

<table>
<thead>
<tr>
<th>Year</th>
<th>% CEVs of cars in traffic</th>
<th>% CEVs of new cars</th>
<th>% Non-CEVs of new cars</th>
<th>% Increase in new CEVs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>0%</td>
<td>2%</td>
<td>98%</td>
<td>306%</td>
</tr>
<tr>
<td>2016</td>
<td>1%</td>
<td>3%</td>
<td>97%</td>
<td>-28%</td>
</tr>
<tr>
<td>2018</td>
<td>1%</td>
<td>6%</td>
<td>94%</td>
<td>30%</td>
</tr>
<tr>
<td>2020</td>
<td>3%</td>
<td>10%</td>
<td>90%</td>
<td>30%</td>
</tr>
<tr>
<td>2022</td>
<td>7%</td>
<td>40%</td>
<td>60%</td>
<td></td>
</tr>
<tr>
<td>2024</td>
<td>23%</td>
<td>100%</td>
<td>0%</td>
<td></td>
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<tr>
<td>2026</td>
<td>40%</td>
<td>100%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>2028</td>
<td>57%</td>
<td>100%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td>73%</td>
<td>100%</td>
<td>0%</td>
<td></td>
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</tbody>
</table>

Table 14: Our projections of the CEV development in Uppsala Municipality, based on historic figures from Myhr (2016a) and own assumptions described in Section 4. Figures before 2013 were not acquired. Table 2 of 2
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## C Appendix - Results

<table>
<thead>
<tr>
<th>Area</th>
<th>Share of CEVs of cars in traffic</th>
<th>25%</th>
<th>75%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Almungebygden</td>
<td>5.1%</td>
<td>2.2%</td>
<td>17.6%</td>
<td>11.7%</td>
</tr>
<tr>
<td>Berthåga</td>
<td>4.2%</td>
<td>1.9%</td>
<td>15.0%</td>
<td>9.3%</td>
</tr>
<tr>
<td>Björklingeområdet</td>
<td>5.1%</td>
<td>2.2%</td>
<td>17.7%</td>
<td>11.8%</td>
</tr>
<tr>
<td>Danmarkshygden</td>
<td>4.9%</td>
<td>2.1%</td>
<td>17.1%</td>
<td>11.1%</td>
</tr>
<tr>
<td>Eriksberg</td>
<td>5.6%</td>
<td>2.4%</td>
<td>19.3%</td>
<td>13.5%</td>
</tr>
<tr>
<td>Flogsta-Ekeby</td>
<td>2.4%</td>
<td>1.2%</td>
<td>9.6%</td>
<td>5.2%</td>
</tr>
<tr>
<td>Fumbygden</td>
<td>5.6%</td>
<td>2.4%</td>
<td>19.3%</td>
<td>13.5%</td>
</tr>
<tr>
<td>Fälhagen</td>
<td>4.9%</td>
<td>2.1%</td>
<td>16.9%</td>
<td>10.9%</td>
</tr>
<tr>
<td>Gamla Uppsala-Nyby</td>
<td>6.0%</td>
<td>2.5%</td>
<td>20.3%</td>
<td>14.6%</td>
</tr>
<tr>
<td>Gamla Uppsalabygden</td>
<td>5.0%</td>
<td>2.1%</td>
<td>17.4%</td>
<td>11.4%</td>
</tr>
<tr>
<td>Gottsunda</td>
<td>7.0%</td>
<td>3.2%</td>
<td>23.5%</td>
<td>18.0%</td>
</tr>
<tr>
<td>Gröndby</td>
<td>7.7%</td>
<td>3.7%</td>
<td>25.4%</td>
<td>20.0%</td>
</tr>
<tr>
<td>Häga</td>
<td>3.7%</td>
<td>1.7%</td>
<td>13.4%</td>
<td>8.1%</td>
</tr>
<tr>
<td>Innerstaden</td>
<td>3.8%</td>
<td>1.7%</td>
<td>13.8%</td>
<td>8.4%</td>
</tr>
<tr>
<td>Järnåsabygden</td>
<td>4.8%</td>
<td>2.0%</td>
<td>16.6%</td>
<td>10.6%</td>
</tr>
<tr>
<td>Knutbyhygden</td>
<td>4.4%</td>
<td>1.9%</td>
<td>15.4%</td>
<td>9.6%</td>
</tr>
<tr>
<td>Kungsängen</td>
<td>9.8%</td>
<td>5.4%</td>
<td>31.9%</td>
<td>27.0%</td>
</tr>
<tr>
<td>Kvarnbåk</td>
<td>4.6%</td>
<td>2.0%</td>
<td>16.1%</td>
<td>10.2%</td>
</tr>
<tr>
<td>Kvarngärdet</td>
<td>5.4%</td>
<td>2.3%</td>
<td>18.6%</td>
<td>12.7%</td>
</tr>
<tr>
<td>Käbo</td>
<td>3.3%</td>
<td>1.5%</td>
<td>12.3%</td>
<td>7.2%</td>
</tr>
<tr>
<td>Librobäck</td>
<td>6.0%</td>
<td>2.5%</td>
<td>20.2%</td>
<td>14.4%</td>
</tr>
<tr>
<td>Luthagen</td>
<td>3.6%</td>
<td>1.6%</td>
<td>13.0%</td>
<td>7.8%</td>
</tr>
<tr>
<td>Lötten</td>
<td>8.0%</td>
<td>3.9%</td>
<td>26.3%</td>
<td>21.0%</td>
</tr>
<tr>
<td>Norby</td>
<td>3.9%</td>
<td>1.8%</td>
<td>14.1%</td>
<td>8.7%</td>
</tr>
<tr>
<td>Norra Rasbohygden</td>
<td>5.1%</td>
<td>2.2%</td>
<td>17.8%</td>
<td>11.8%</td>
</tr>
<tr>
<td>Nåntuna-Vilan</td>
<td>4.3%</td>
<td>1.9%</td>
<td>15.3%</td>
<td>9.5%</td>
</tr>
<tr>
<td>Rickomberga</td>
<td>8.3%</td>
<td>4.1%</td>
<td>27.1%</td>
<td>21.8%</td>
</tr>
<tr>
<td>Sala backe</td>
<td>7.6%</td>
<td>3.7%</td>
<td>25.3%</td>
<td>19.9%</td>
</tr>
<tr>
<td>Skyttorpsbygden</td>
<td>4.8%</td>
<td>2.1%</td>
<td>16.7%</td>
<td>10.6%</td>
</tr>
<tr>
<td>Stenhagen</td>
<td>5.5%</td>
<td>2.3%</td>
<td>18.7%</td>
<td>12.9%</td>
</tr>
<tr>
<td>Storvretabygden</td>
<td>4.9%</td>
<td>2.1%</td>
<td>17.2%</td>
<td>11.2%</td>
</tr>
</tbody>
</table>
Table 15: Increase in max load (%) for different CEV shares of cars in traffic for all areas in Uppsala Municipality. Ho. = House, Apt. = Apartment

<table>
<thead>
<tr>
<th>Area</th>
<th>Unweighted average</th>
<th>Apt.</th>
<th>Ho.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunnersta</td>
<td>4.6% 2.0% 16.2% 10.2% 19.7% 13.9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Svarthäcken</td>
<td>5.9% 2.4% 19.9% 14.1% 24.1% 18.6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sävja-Bergsbrunna</td>
<td>5.6% 2.3% 19.1% 13.3% 23.2% 17.7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Södra Hagundabygden</td>
<td>5.1% 2.2% 17.7% 11.8% 21.5% 15.9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Södra Rasbobygden</td>
<td>5.4% 2.3% 18.5% 12.6% 22.4% 16.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tuna backar</td>
<td>6.2% 2.5% 20.9% 15.1% 25.3% 19.9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ulleråker</td>
<td>8.1% 4.0% 26.6% 21.3% 32.2% 27.3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultuna</td>
<td>2.3% 1.2% 9.3% 4.9% 11.4% 6.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vaksalabygden</td>
<td>5.6% 2.3% 19.1% 13.3% 23.2% 17.7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valsättra</td>
<td>5.0% 2.1% 17.2% 11.2% 20.9% 15.2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vattholmabygden</td>
<td>5.0% 2.1% 17.4% 11.4% 21.1% 15.4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vårdsättra</td>
<td>5.1% 2.2% 17.6% 11.7% 21.4% 15.7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vängebygden</td>
<td>5.2% 2.2% 18.0% 12.0% 21.8% 16.1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Västra Bälingebygden</td>
<td>5.3% 2.2% 18.3% 12.4% 22.2% 16.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Årsta</td>
<td>6.8% 3.0% 22.9% 17.3% 27.7% 22.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Östra Bälingebygden</td>
<td>5.3% 2.2% 18.1% 12.2% 22.0% 16.4%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cars per

<table>
<thead>
<tr>
<th>Area</th>
<th>Apt.</th>
<th>Ho.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unweighted average</td>
<td>0.37</td>
<td>1.39</td>
</tr>
<tr>
<td>Almungebygden</td>
<td>0.35</td>
<td>1.33</td>
</tr>
<tr>
<td>Berthåga</td>
<td>0.30</td>
<td>1.14</td>
</tr>
<tr>
<td>Björklingeområdet</td>
<td>0.36</td>
<td>1.34</td>
</tr>
<tr>
<td>Danmarksbygden</td>
<td>0.34</td>
<td>1.29</td>
</tr>
<tr>
<td>Eriksberg</td>
<td>0.39</td>
<td>1.45</td>
</tr>
<tr>
<td>Flogsta-Ekeby</td>
<td>0.20</td>
<td>0.76</td>
</tr>
<tr>
<td>Funbobygden</td>
<td>0.39</td>
<td>1.45</td>
</tr>
<tr>
<td>Fälhagen</td>
<td>0.34</td>
<td>1.28</td>
</tr>
<tr>
<td>Gamla Uppsala-Nyby</td>
<td>0.41</td>
<td>1.52</td>
</tr>
<tr>
<td>Gamla Uppsalabygden</td>
<td>0.35</td>
<td>1.31</td>
</tr>
<tr>
<td>Gottsunda</td>
<td>0.46</td>
<td>1.74</td>
</tr>
<tr>
<td>Grünby</td>
<td>0.50</td>
<td>1.88</td>
</tr>
<tr>
<td>Häga</td>
<td>0.28</td>
<td>1.03</td>
</tr>
<tr>
<td>Innerstaden</td>
<td>0.28</td>
<td>1.06</td>
</tr>
<tr>
<td>Järlasabygden</td>
<td>0.34</td>
<td>1.26</td>
</tr>
</tbody>
</table>

120
Table 16: Number of cars per household in Uppsala areas. Ho. = House, Apt. = Apartment

<table>
<thead>
<tr>
<th>Area</th>
<th>Ho.</th>
<th>Apt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knutbybygden</td>
<td>0.31</td>
<td>1.17</td>
</tr>
<tr>
<td>Kungsängen</td>
<td>0.62</td>
<td>2.34</td>
</tr>
<tr>
<td>Kvarnbo</td>
<td>0.33</td>
<td>1.22</td>
</tr>
<tr>
<td>Kvarngårdet</td>
<td>0.37</td>
<td>1.40</td>
</tr>
<tr>
<td>Kåbo</td>
<td>0.25</td>
<td>0.95</td>
</tr>
<tr>
<td>Librobäck</td>
<td>0.40</td>
<td>1.51</td>
</tr>
<tr>
<td>Luthagen</td>
<td>0.27</td>
<td>1.01</td>
</tr>
<tr>
<td>Löten</td>
<td>0.52</td>
<td>1.95</td>
</tr>
<tr>
<td>Norby</td>
<td>0.29</td>
<td>1.08</td>
</tr>
<tr>
<td>Norra Rasbobygden</td>
<td>0.36</td>
<td>1.34</td>
</tr>
<tr>
<td>Nåntuna-Vilan</td>
<td>0.31</td>
<td>1.16</td>
</tr>
<tr>
<td>Rickomberga</td>
<td>0.53</td>
<td>2.00</td>
</tr>
<tr>
<td>Sala backe</td>
<td>0.50</td>
<td>1.87</td>
</tr>
<tr>
<td>Skyttorpsbygden</td>
<td>0.34</td>
<td>1.26</td>
</tr>
<tr>
<td>Stenhagen</td>
<td>0.37</td>
<td>1.41</td>
</tr>
<tr>
<td>Storvretabygden</td>
<td>0.35</td>
<td>1.30</td>
</tr>
<tr>
<td>Sünnersta</td>
<td>0.33</td>
<td>1.23</td>
</tr>
<tr>
<td>Svartbäcken</td>
<td>0.40</td>
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</tr>
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<td>Sävja-Bergsbrunna</td>
<td>0.38</td>
<td>1.44</td>
</tr>
<tr>
<td>Södra Hagundabygden</td>
<td>0.36</td>
<td>1.34</td>
</tr>
<tr>
<td>Södra Rasbobygden</td>
<td>0.37</td>
<td>1.39</td>
</tr>
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<td>Tuna backar</td>
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<td>0.74</td>
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<td>1.44</td>
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<tr>
<td>Valsättra</td>
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<td>1.30</td>
</tr>
<tr>
<td>Vattholmabygden</td>
<td>0.35</td>
<td>1.31</td>
</tr>
<tr>
<td>Vårdsättra</td>
<td>0.35</td>
<td>1.33</td>
</tr>
<tr>
<td>Vängebygden</td>
<td>0.36</td>
<td>1.35</td>
</tr>
<tr>
<td>Västra Bälingebbyn</td>
<td>0.37</td>
<td>1.38</td>
</tr>
<tr>
<td>Årsta</td>
<td>0.45</td>
<td>1.70</td>
</tr>
<tr>
<td>Östra Bälingebbyn</td>
<td>0.36</td>
<td>1.37</td>
</tr>
</tbody>
</table>