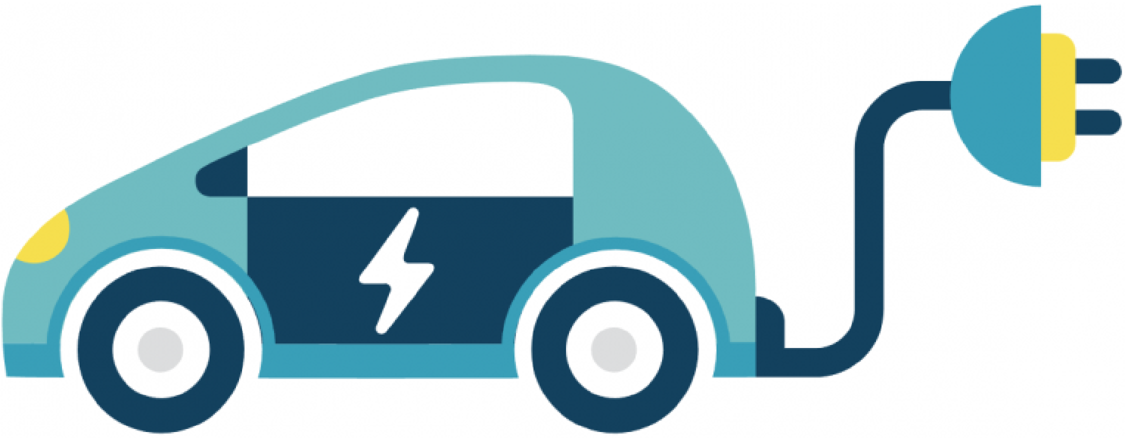
Electric Vehicles

Will they break the future Danish electricity grid?



MASTERS THESIS
SUSTAINABLE ENERGY PLANNING AND MANAGEMENT
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Abstract:

This thesis is based in Choice Awareness Theory in order to offer different choices in relation to the future prospect of increased EV power demand. Through the use of a custom made Excel model, different scenarios of residential EV population are explored, both for the distribution grid and the transmission grid in Denmark, in an attempt to answer the question of what would happen to these grids, and if they would break. The results point towards both grids being stronger than anticipated; but the distribution grid is ill-equipped to handle large volumes of EVs, although the transmission grid is unlikely to break at all as a result of increased EV population. Expansion of the model by way of commercial transportation or financial considerations might improve the accuracy of the results. The negative aspects of the findings can be countered by preparing the respective grids for the increased demand.

Abstracts

English: This thesis is based in Choice Awareness Theory in order to offer different choices in relation to the future prospect of increased EV power demand. Through the use of a custom made Excel model, different scenarios of residential EV population are explored, both for the distribution grid and the transmission grid in Denmark, in an attempt to answer the question of what would happen to these grids, and if they would break. The results point towards both grids being stronger than anticipated; but the distribution grid is ill-equipped to handle large volumes of EVs, although the transmission grid is unlikely to break at all as a result of increased EV population. Expansion of the model by way of commercial transportation or financial considerations might improve the accuracy of the results. The negative aspects of the findings can be countered by preparing the respective grids for the increased demand.

Dansk: Denne afklaring baseres i Choice Awareness Theory for at fremstille forskellige valg i forbindelse med fremtidens mulige stigning i antallet af elbiler i Danmark. Ved hjælp af en model lavet i Excel, vil forskellige scenarier af den personlige elbil-bestand og type blive udforsket, både for distributions- og transmissionsnettet, i et forsøg på at besvare spørgsmålet om hvad der ville ske ved disse elnet, og om de ville holde til det øgede forbrug. Resultaterne peger mod at begge elnet er stærkere end forventet, men distributions-nettet er ikke velforberedt til at håndtere en stor mængde elbiler, hvor transmissionsnettet i stedet ikke ser ud til at komme til at opleve problemer. Modellen kunne udvides med industriel transport, eller finansielle overvejelser, for yderligere at udforske modellen. De negative resultater kan blive modvirket med et velforberedt elnet i begge tilfælde.

Preface

The basis for this thesis came from my interest in making models and working on in-depth analyses, and through my interest in electric vehicles and the incredibly exciting future of transportation as we move away from fossil fuels. I was curious if the danish grids could handle the potentially sudden increase in demand caused by large-scale adoption of EVs instead of fossil fueled vehicles. I could not have written this thesis without the unwavering support of my wife, or the support of my supervisor who frequently answered questions at all hours and provided feedback and help throughout the process of this thesis.

Nomenclature

Abbreviations

AAU	Aalborg University
DoD	Depth of Discharge
DSO	Distribution System Operator
EV	Electric Vehicle
SoC	State of Charge
TSO	Transmission System Operator

Units

$CO2$	Carbon Dioxide
GW	Gigawatt
GWh	Gigawatt Hour
K	Thousand
km	Kilometer
kW	Kilowatt
kWh	Kilowatt Hour
MW	Megawatt
MWh	Megawatt Hour
TW	Terawatt
TWh	Terawatt Hour

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1 Introduction

This thesis attempts to address the future issue of electrified transportation, and how this will impact the future electrical grid in Denmark. The transportation market is steadily heading towards full electrification. This means that large parts of the current energy amount spent on transportation through fossil fuels will be moved to the electric grid instead. Current electric vehicles (EV) have a relatively slow charge speed, compared to the technology in development, and they have a relatively low capacity compared to these new models. This means that upcoming EVs will charge significantly faster, as well as have significantly increased capacities. [Lambert, 2017]

The driving force behind this development is an effect known as climate change. Climate change is the effect caused by pollution, such as CO2 emissions, particulates, and others. These are emitted by many different industries, and it is an effect that most nations worldwide seek to combat, in a variety of ways. One of the largest contributors to climate change is the transport sector, and there is a significant push worldwide towards greener alternatives to personal transportation, as well as other sectors of transportation. Battery-powered electric vehicles are among these, as are alternative fuels. This thesis is not addressing the other fuel types, and will focus on battery-powered vehicles only. [NASA, 2018; Kunkel et al., 2013a,b; Church and White, 2006]

The current fastest charging stations support up to 175 kW, and might soon support up to 350 kW [Lambert, 2017], and there are EVs on the way to market that support up to 500 kW charge speeds [Toshiba, 2017]. Depending on the amount of EVs that will be available, the amount of power demand suddenly added might significantly impact the current electric grid. The most extreme scenario mentioned in prognoses is 500,000 (500K) EVs by 2025 [Malfelt, 2010]. This thesis will also attempt to look beyond the year 2025, at what might happen if all vehicles used for personal transportation in Denmark get exchanged for electric powertrains.

Norway has already experienced issues with EVs, due to a sudden spike in adoption and availability of EVs. These issues are experienced mostly in rural areas, where demand has gone up fast, due to the distribution networks not being able to handle the sudden increase in demand, caused by EVs charging at home, and the availiability of more powerful home charging stations [Spindler, 2014a; Clever, 2018]. Furthermore, Norway is expecting even more demand, and therefore they need to consider other methods of covering this increase in demand [Spindler, 2014a; Berggreen, 2017; Noel et al., 2017]

Problem Description 2

The transport sector is heading towards electrification, and one of the key fields of this transition is in personal transport. The increase of EV availability, coupled with the power requirement that they have, can eventually cause problems for the electrical grid. This grid exists on two main levels, the transmission level, and the distribution level. The transmission level is the "grid", the main power infrastructure between areas of the country, and connects major producers and consumers, it is very stable, and carries high voltage. Stability in this case denotes the ability to handle large peaks and dips in consumption through up- and downregulation of production. The distribution grid on the other hand, is a smaller grid, that serves low-power requirements, such as homes, smaller businesses etc. This means that the distribution grid is inherently weaker as it is not designed to handle large peaks and dips in demand, but instead designed for supply stability. Due to the high power requirement that EVs have, they can cause issues for the distribution grid, if enough of them are charging at the same time. This is a problem that has been evident in Norway, where the distribution grid in certain places experienced cutouts and temporary blackouts caused by too many EVs charging at the same time [Berggreen, 2017].

The transmission grid however, is stronger, and can handle larger peaks and dips in consumption, such as EVs charging. Although the transmission grid might experience its own issues, due to the high power that the transmission grid can deliver, equally high power charging stations appear. There are currently stations being installed in Europe, that allow for a theoretical 350 kW charging [Lambert, 2017]. These stations could cause issues if a lot of EVs charge at the same time. This problem is made evident when looking at a prediction made for the EV population in Denmark, as 500K by 2025 [Malfelt, 2010]. If we then assume that at peak hours, 20% of that amount would be charging simultaneously, that would be 100K EVs charging at 350 kW, putting the total strain on the grid at 35 GW, which exceeds the grids maximum capacity of 16.7 GW as of 2015 [Danish Energy Agency, 2014]. Although this is very unlikely to happen, it serves to illustrate that while 350 kW on its own is not necessarily an issue, once the amount of EVs on the roads increases, more and more issues might occur, which is what will be explored in this thesis.

2.1 Transmission vs Distribution grid

The electricity grid is split into two major parts, the transmission level - often called the "highway" - and the distribution grid "the small roads", the transmission level is the high capacity level that sends power from power plants to the major power consumers, which include the companies supplying electricity to ordinary consumers, such as residential. The distribution grid is the grid that serves low-power consumption, such as households, smaller businesses and other low-power applications. The distribution grid is also a bit of a misnomer, due to it not being a singular thing like the transmission grid is. Each neighbourhood has its own grid, and each city has its own subgrid as well. That means that the distribution grid has a lot of smaller components, various levels of transformers, that each have to be upgraded if power demand should suddenly rise. The transmission grid on the other hand relies on significantly fewer components. [Danish Energy Agency, 2015, 2014]

Although it was mentioned that the transmission grid is a singular thing, it should be noted that the danish transmission grid is split into two major parts, DK-West and DK-East, where the "bridge" is at the end of the Storebælt bridge. These two grids are synchronized in frequency but are nonetheless not directly connected, and are therefore in everyday concerns, two different markets, and any transfer between them need to go through the "bridge", which itself has a maximum transfer capacity. DK-East is further directly connected with Sweden. DK-West is the grid with the most production, and is the grid that is connected with import and export cables to Germany and Norway. [Danish Energy Agency, 2014]

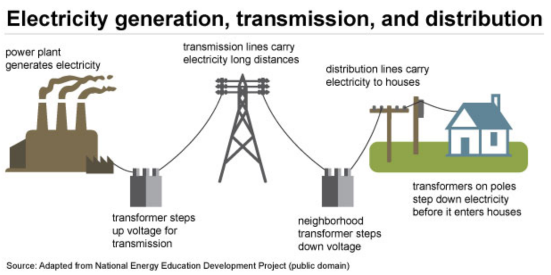


Figure 2.1: Model of electricity delivery [EIA, 2018]

The distribution grids in Denmark are not as easily mapped, as they are often owned by the respective utility companies of a given area, and therefore are subject to private company laws. N1 is the company that owns the distribution grid that includes Aalborg, and large parts of mid-Jutland, they offer a visible map of their network, and the voltage of their transformers, but they do not provide any peak information such as maximum amperes, which is necessary to identify its maximum wattage. Due to this, the distribution grid model in this thesis bases its data from a thesis from Norway, exploring a specific neighbourhood in rural Norway. [Spindler, 2014a; N1, 2018]

This thesis does not consider economic aspects of upgrading either system should it become necessary, therefore there will be no analysis of which scenario is cheapest. But the main argument in terms of the grids, is that the transmission grid is better suited to handle and expand into the future electric transportation sector, mainly due to its ability to efficiently adapt to large fluctuations in demand caused by high-power EV charging. Simply put, building central, high-power charging stations should be simpler and less expensive to power if it is attached to the transmission grid, rather than have to expand the distribution grid to accomodate it, or to accomodate a significant amount of home-charging EVs.

2.2 Problem statement

The main focus of this report, is the problem of an expected surge in EV sales during the next decade, and how this will impact the electrical grid. Current consumption and production figures will be used as basis to model different future scenarios, as well as different prognoses of how many EVs will be sold within the decade. This means the problem statement is as follows;

"How will EVs impact the future electricity grid, and what is the most efficient way to deal with it?"

To help triangulate the issue, these sub-questions will be used;

- What would the grid look like with different amounts of EVs?
- How many EVs will "break" the grid?
- Is the transmission grid better than the distribution grid for EV charging?

2.2.1 Delimitations

This project will not cover every type of EV available, and will only cover EVs for personal transportation; EVs for commercial transportation will not be a part of this analysis.

Choice Awareness Theory 3

This thesis makes use of Choice Awareness Theory [Lund and Quinlan, 2014] as its theoretical framework. Choice Awareness Theory builds upon the principle of *real choice* versus *fake choice*. What this means is that according to the theory, society often experiences or is exposed to situations in which there is "no choice but to..", indicating some level of forced response to a given situation. For example, Lund mentions that DONG Energy once released an article which stated that to achieve CO2 neutrality by 2050, Denmark had *no choice* but to employ carbon-catching systems in their coal-fired power plants, essentially stating that Denmark could not go on without the coal-fired power plants, that they owned. In this scenario, an institution with a vested interest in keeping a specific technology alive, posited a *no-choice* scenario in which Denmark would be forced to keep going with a technology, that Lund found evidence explaining that that was not the case, necessarily. Simply put, Lund implies that there is always a choice, even though it may not seem immediately obvious, it is important that people are aware that they always have a choice, and that the other choices are not necessarily as bad as the institutions in power attempt to state they are. [Lund, 2014]. *Fake choice*, in the context of the theory, is used when two or more choices are presented, but one of them is not really a choice, such as "This horse or none", which posits that either you choose the horse that is presented, or none at all, effectively making it a *no-choice* scenario, where the recipient is posited with either having the horse currently presented, or none at all, while there may, in fact, be many other horses available for purchase. [Lund, 2014]

The relevance comes in the presentation of choice, currently, companies are free to choose in which way they offer their respective solutions for EV charging, some companies offer stronger and stronger home charging [E-ON, 2018; Clever, 2018], and other companies offer centralized charging stations [Lambert, 2017].

Choice Awareness relates to this thesis in a different way, as there is no claim that there are institutions at play which are attempting to make it seem as if there are no choices in relation to EVs. If a transition away from fossil fueled cars is intended, there are a variety of choices to complete this. For example, there are vehicles that drive on electricity, but gain their energy from alternative fuel sources, such as hydrogen and methanol [EPA, 2017]. This means that it is not only battery-powered EVs that can be used, other fuel sources are also available, but present with their own list of pros and cons. This thesis will not attempt to cover these alternative fuels, but it is important to mention in the context of choice awareness, as they might offer a competitive solution to simply charging batteries. This thesis however, will focus on a different area of choice; how to deal with battery-powered EVs. The reason that the focus is kept on battery-powered electric vehicles, is due to them potentially posing a significant threat to the electricity grid, in addition to steadily growing sales numbers for these vehicles [International Energy Agency, 2018]. Norway is already experiencing issues with the current state of EVs, specifically supplying demand on the distribution grid, for home charging. [Spindler, 2014b; Noel et al., 2017; Berggreen, 2017]

Denmark does not currently have a significant amount of EVs, only 9,111 as of this year [Danske Elbil Alliance, 2017]. This number however, is expected to rise significantly in the coming years, partly due to government policies, but also increased availability and as such, lowered costs [Malfelt, 2010]. Norway currently has roughly 120K EVs, and they're experiencing issues [Noel et al., 2017]. The prognosis mentioned in [Malfelt, 2010] originally estimated 500K EVs on Danish roads by 2025, but has since modified that prognosis to 400K. This is still a significant amount in comparison to the 120K EVs that are currently in Norway, and therefore it might also cause issues for the Danish electric grid if that many - and more - EVs come online.

This relates back to Choice Awareness since it is currently common to believe that EV owners can just charge at home, and therefore it seems as if strengthening the distribution grid is the only solution [Spindler, 2014b; E-ON, 2018; Spoelstra, 2014; Turrentine et al., 2011]. This is of course, a choice, and expanding the distribution grid is possible, especially if the DSO's are warned in advance. But it is not the only choice, there is also the possibility of treating EVs and their energy needs the same way that fossil cars are treated today, centralized charging stations. Simply put, by disallowing high-power home chargers, in favor of ultra-fast central stations connected to the transmission grid, might provide a more feasible implementation. The transmission grid is stronger than the distribution grid, as mentioned in section 2.1, and therefore is better suited to handling the significant peaks and dips in consumption that ultra-fast charging could cause.

This thesis aims to visualize two paths of choice, based upon prognoses, the distribution grid and the transmission grid, and the pros and cons of either. Both grids will be modelled with the expected impact of the EVs, and benefits as well as downsides will be discussed, in relation to Choice Awareness.

Methodology 4

This thesis builds upon the argument that the distribution grid is not the optimal energy delivery system for electrified transportation, due to risk of grid overload, and therefore risk of losing supply security. The focus is therefore on building the framework to support efficient high-speed charging stations, connected to the transmission grid, to enable strong supply security, safety, and convenience for EV users. In order to do this, the current grid will be used as a modelling baseline, in a time-step fashion. Then, using current refueling patterns for fossil-based vehicles, as charge patterns for EV users, a potential future scenario will be modelled. The parameters for this modelling include; Distribution patterns, average driving distance, average EV consumption per km, charge speeds, charge times, charging hours (including night charging), statistical percentage of concentration of EVs, distribution grid transformers and consumption.

Each of the aspects of the methodology used in this report will be elaborated below, starting with the model itself and what the goals of it are. Each major parameter will be elaborated and expanded upon, and discussed. This is so as to give a clear picture of what is going to be analyzed, and what the expected impact of it is, and the usefulness of it, including a specific section about how to model the distribution grid, considering the lack of data availability mentioned previously. Then, alternatives to the model will be presented and explained as to why they were not picked for the purpose of this thesis. Lastly, the actual math used in the model will be presented, so that anyone can attempt to make their own models based on the calculations, for the sake of verification and scrutiny.

4.1 The Model

The model is at the core of the methodology, the goal of the model is to offer a potential framework which can be extended upon as necessary to cover the increased demand from EVs, in a way that consumers will be inconvenienced as little as possible, while retaining supply stability. This means that the model will have to describe how central charging stations should be set up - from an energy planning perspective - so that any new station can be built according to this model, and supply the power necessary to cover demand. For this to work as intended, a large variety of data points need to be included, such as the earlier mentioned parameters. The reason that the model is seen as the goal, is because the future is as yet unknown, and there are only prognoses as to what will happen within the next decade. It is uncertain how fast the population will adopt EVs, nor is it known how fast these EVs will actually charge, or how often they will charge. Because of this, the data used in the model is based on extrapolations of current data, and in some cases, based on social trends. This allows the model to be expanded to include future data.

The model is constructed in such a way that any new data can easily be added to increase precision, new distribution data, consumption data, EV data, population data and soforth can all be added, and updated as more information comes in. Furthermore, the model will display the total expected added demand, the total visitor count as expected, and how much peak demand they will add. Therefore, as more data comes in, the model will become more precise as a result. This model will answer the problems posed in the problem statement, as it can offer insights into how many cars will break the grid, how the grid will likely look with the added demand, and when to expect issues with the different grids.

Lastly, to limit the scope of this project, specific EVs will be used as data points for different impacts, depending on efficiency and battery size. Three vehicles have been picked for this purpose, based upon a list of the most popular EVs sold in Denmark from [Sparre and Buch, 2017], which consist of the Renault Zoe, the BMW i3, and the Tesla Model S. Consumption data is gathered from publicly available commercial material [Renault, 2018; Volkswagen, 2018; Tesla, 2018]. It should be noted here that the Zoe and the i3 are fairly similar in their statistics, but they are both included as they are the two most popular vehicles in Denmark. The Tesla instead serves as the contrasting vehicle, being the least efficient, as well as being the 3rd most popular. Table 4.2 showcases the data points gathered from the previously mentioned sources. The vehicle efficiencies are further corroborated by the NEDC (New European Driving Cycle), which tests all EVs and their efficiencies [NEDC, 2018]. However, the NEDC very often reports higher efficiencies than can be realistically expected from the vehicles in question, which also affect analysis results. Volkswagen openly admits to this in their brochure, that the NEDC rating is far higher than can be reliably expected from the vehicle [Volkswagen, 2018]. In the brochure for their EV, the e-Golf, it clearly states that while the NEDC reports a 300km range for the vehicle, the realistic range is likely around 200km, and that consumers should not expect the NEDC data to be a correct measurement of the vehicles range [Volkswagen, 2018]. However, due to the fact that user-reported efficiences are often anecdotal and only reflect that given consumers consumption - irrespective of driving habits - the NEDC results are used for modelling. The result of this is that the visitor count for each hour is likely lower than what would be seen due to the lower realistic efficiency of each vehicle.

Table 4.2: Vehicle Statistics

	Renault Zoe	BMW i3	Tesla Model S
Battery size in kWh	42	40	100
Efficiency in kWh/100km	13.3	12.6	20.6

4.2 The "Right" Distribution Pattern

EVs are still very early in adoption stages, and current charging pattern data is limited. It is based mostly around early adopter behaviour, which does not necessarily reflect the behaviour of the general consumer. This thesis is made on the assumption that EV drivers will behave largely like current fossil-car drivers, because current fossil-drivers have developed their behaviour over time, and will likely want to continue this behaviour. Currently, you always have to stop at a fuel station to refuel your vehicle, as it is not feasible to have a fueling station at home. This means that the average driver is used to having to plan routes that include refueling stations when needed. This should therefore reflect in distribution patterns as well, which means that for distribution purposes, refueling patterns for fossil vehicles can be used.

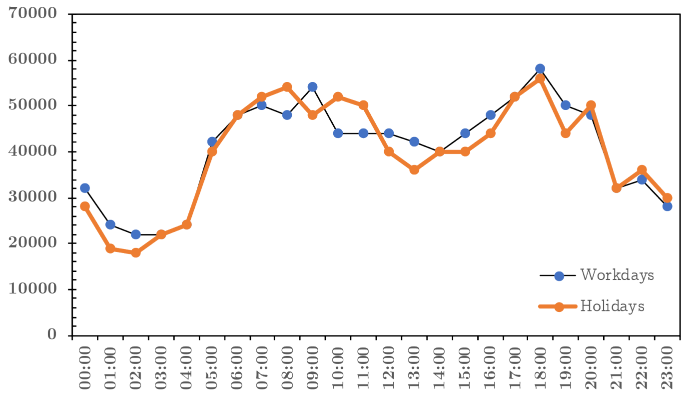


Figure 4.1: Gas Station Visitors [Zhang et al., 2015]

It could be argued however, that because EVs function very differently than fossil cars. As a consumer, the fuel source is already located at home, although with much slower speed, it might seem natural to just "refuel" at home, when you're not using the vehicle anyway. This use pattern however, comes with a few disadvantages. Charging at home takes significantly more time than charging at designated fast-charging points. As mentioned earlier, charging at home charging stations can cause significant stress on the distribution grid, as it is not currently built to handle such large - and recurrent - peaks in demand. But from the perspective of modelling, EV charging patterns seem like the more obvious choice of distribution data, even despite these issues. Spindler [2014a]

The main focus of this thesis is the technical feasibility of centralized charging stations for EV consumers, and for that reason, fossil-car distribution patterns are chosen as main baseline. Since the distribution grid will also be modelled, a simplistic version of charging will be used instead. Specifically, it is assumed that consumers will plug their vehicle in when they come home from work, and unplug when they leave for work, leaving the car to charge for 8-12 hours. Granted, these vehicles will not always need the full 12 hours to recharge, but the main point of interest is the plug-in time, and the peak that it generates, versus how it would look if equally distributed across the 8-12 hour timespan that the consumers are at home. [Zhang et al., 2015; Kitamura and Sperling, 1987]

4.3 Calculating EV consumption

Consumption data is the next issue. There are a few ways to model future consumption, but since we are talking about uncertain future data points, we again have to extrapolate from current data. The data chosen for extrapolation is based on fossil-cars again. Current EVs have efficiencies, which in EV terms is noted as kWh/100km, or how many kWh is on average spent per 100km driven. This, coupled with data on average driving distance per year, per person, can give a rough estimate as to how much a given EV will have to charge in a day. However, this also contains some assumptions. Not every fossil-car owner refuels every day, so for the purpose of modelling, only a percentage of EV owners would charge their car in a given day, but this too is based on assumptions, as it is not known how many EV owners will charge their car in a given day. The average driver does not drive the same distance every single day, but this is also a complete uncertainty, therefore averages are used. It is also assumed that EV drivers will average the same distance driven per year as with fossil cars, even though there are most likely a variety of reasons that the average driving distance is the way it is currently. For example, the prices of electricity make EVs significantly cheaper to run than fossils, so perhaps owners will be more likely to drive them more often. Furthermore, other external factors of future drivers might also change the charging frequencies, such as availability of public transportation. While the math will be presented later in this chapter, the short version is that the efficiency of the given EV is put up against the average annual driving distance and the state-of-charge upon recharging, to figure out how often a given owner would recharge their vehicles, ranging from every other day to several days between charges.

4.3.1 Prognosis

There are different prognoses available from different sources, and they vary. Adding to this uncertainty is the fact that the current amount of EVs in Denmark is 9,111 cars, a figure that makes most prognoses - for the year 2025 anyway - seem unrealistic. This means that there is a lot of uncertainty regarding the number of EVs that will be on the road going forward, so this is also left to educated guesses and prognoses based upon a variety of factors. For the purpose of modelling, two prognoses will be used: 500K EVs and a full electrification scenario of 2.5 million EVs, replacing all current personal vehicles on the road. That last scenario is included as a means to test the model, to see if the grids can realistically cope with a total electrification of the personal transport sector. As for the distribution grid, it will rely on a percentage based statistic of how many households would own an EV, on average, in the given scenarios.

4.4 State of Charge

Just as current fossil car owners refuel before they have a completely empty tank, it can be expected that EV owners will want to recharge before they run out of battery. This also means that for the purpose of modelling, higher accuracy can be attained by accounting for the fact that the EVs will not be completely empty when plugged in, which is also a recommended practice to keep the battery healthy [Battery University, 2018a]. Furthermore most fast chargers only fast charge to about 80-90%, due to Lithium-Ion batteries being inherently slow to fully charge [Battery University, 2018a]. However, it can be hard to decide what percentage to use as the minimum state-of-charge (SoC), as the behaviour of EV owners in that regard has not been fully researched yet. Furthermore, EV owners can differentiate a lot depending on how much they're willing to let the car discharge before recharging it again. It is commonly known that lithium-ion batteries cannot handle being fully discharged, but most battery manufacturers account for this when they produce their batteries, and therefore they build in circuitry to make sure that the cell stops working when reaching dangerously low voltage [Battery University, 2018b].

Due to the difficulty of finding correct information on common depth of discharge for EV owners, and same difficulty finding accurate refueling data for fossil cars, the minimum SoC will be assumed, and worked with. To account for imprecision, three different levels of SoC's will be used; 10% (ultra-low), 25% (quarter tank), and 50% (half-tank). These numbers have been chosen to illustrate different approaches to recharging, and they will in turn impact how often EVs will need to recharge. The 10% scenario is considered ideal in this context, as the longer a consumer drives before wanting to recharge, the longer it'll take between recharges, and therefore lower the amount of concurrent visitors and recharge stations at any given hour. Ideal scenarios however, are often not the most realistic, and it can be expected that not all owners will act the same way.

By including the state of charge, a more accurate representation of hourly visitors is achieved, but it has no impact on the total energy demand that the vehicles will generate, as that depends entirely upon the vehicle efficiency and annual driving distance. Therefore the state of charge related data is only relevant for concurrent visitor count, and therefore peak demand, and not for the total energy demand, as will be explored further in the analysis chapter.

4.5 Upcoming technology

Another factor to consider with this model is upcoming technologies that have been announced and are possibly already on the way to market, that may or may not change the EV landscape. Examples of such technological advances is the Toshiba EV battery [Toshiba, 2017]. Toshiba have stated that this battery is capable of charging 320 km worth of range in just 6 minutes. They provide a chart for easy comparison between different models of EVs on their site, and with this chart, it's possible to calculate that the battery is capable of receiving roughly 320 kW, until it reaches around 91% capacity, at which point it reaches the bottleneck of all lithium-ion batteries, namely the top percentages, that cannot be fast-charged [Toshiba, 2017; Battery University, 2018a]. However it also seems that it can charge similar distances as other batteries claim, which would mean that it would charge 5 times faster, as $6*5 = 30$, so 6 minutes compared to 30 minutes. This would logically mean that the battery could charge at upwards of 500 kW, 5 times faster than the 100 kW chargers. The point is that they do not specify the actual charge speed, and therefore, it is an educated guess about the top charging speed. Tech like this would mean that within a relatively short timeframe, EVs could go from charging at a maximum of 100 kW (in the case of Tesla), to 320 kW, and there are already charging stations being built that are capable of delivering up to 350 kW of power. Technologies like these could significantly increase the stress on the grid, because of the massively increased charge speed, and also the charge time, dropping from an average of 30 minutes for fast charging, to just 6 minutes [Lambert, 2017]. This cut-down in charge time combined with the increase in charge power, could mean even larger peaks and dips in consumption than planned for.

This thesis will attempt to consider both the normal, current charge scenarios of 30 minute charges at 100 kW max, and the extreme scenario, of 6 minute super high-power charging.

4.6 Distribution Grid Modelling

Because of the distribution grid being mostly private, in the sense that many consumers connected to a distribution grid fall under "private" category, and therefore the data is not readily available for modelling, guesses have to be made. During the process of writing this thesis, it was not possible to get information on an average distribution transformer in Denmark, nor was it possible to get any relevant consumption data. Therefore the data from the transmission grid is used and simply divided down to individual households, and then, the example from [Spindler, 2014b] is used as a baseline. Because of the lack of consumption data, a distribution data set was not available for extrapolation either, so the model works from the assumption that EV owners will come home at 17:00 from work and plug in their vehicle when they arrive, to their respective charging stations. The goal is not so much to accurately display the real life consumption, but instead to display what would happen if a set amount of owners plug in their vehicles upon coming home, in the attempt to illustrate a certain "breaking point". So therefore, in the analysis, the distribution grid will be displayed as a simple factor of concentration of EVs - as in how many of the households own an EV - and what the peak demand might be if they owned different types of home charging stations, based upon information gathered from [E-ON, 2018; Clever, 2018], as well as the transmission scenario EV population.

A testing distribution transformer is used as a theoretical ceiling for power consumption, it is used to illustrate at which point power delivery becomes critical and causes risks of black- or brownouts. The distribution scenario mentioned in the Norway report is that one transformer of 300 kW capacity, serves 25 households, 25 cabins, and 11 commercial buildings. Due to lack of data availability for average commercial consumer consumption, and low difference between households and cabins in this scenario in terms of electricity consumption, this theoretical Danish neighbourhood is one with 60 households - rounded down - attached to a 300 kW capacity transformer. It serves to very roughly illustrate the comparative impact a given distribution of EVs would cause.

In an attempt to locate the amount of EVs these households would own in a given scenario, the total amount of EVs is divided with the total amount of households in Denmark [Danmarks Statistik, 2018], to get a statistical percentage of how many households in Denmark own an EV, and therefore how many households in the scenario owns an EV. Then, it is assumed that the owner of the EV comes home from work at 17, and the vehicles stay plugged in until the morning after. The choice of evening or night hours is fairly arbitrary as it appears that normal consumption is not that significantly different in the evening hours aside from a small peak at 17, which is why the hour of 17 was chosen, although the difference between the hours, according to the data that was found, is not significant enough to cause a massive difference between which hour was chosen. The math mentioned earlier will be elaborated further at the end of this chapter.

4.7 Time-Step Modelling

The time-step modelling method will be used for the purpose of accuracy, when modelling the different EV scenarios, with regard to charge hours and distributions. The time-step is measured in hours over the course of a year, and the year 2017 in Denmark will be used as a baseline for modelling purposes. The data for the production and consumption of electricity in this year is readily available from Energinet, in hourly format. Therefore it also serves as an easier method to work with and extrapolate the necessary data for the other parts of the analysis. However each day of the year is aggregated to each hour to simplify presentation, so while the graphs only show a 24 hour period, they do infact base their data on the full year of consumption, each hour being the highest consumption hour of the year, to strengthen the illustration of peak hour plus added demand.

There are many different tools that allow for time-step modelling, but due to the needs for extrapolation and other data treatment measures, the model will be made by hand in Microsoft Excel. This gives more control over the specific calculations and assumptions necessary to extrapolate said data, as well as the possible overview of each step in the model process. Furthermore, other models have - as mentioned - different goals than the thesis aims for, and are therefore not as well suited for use. The models that compete are for example EnergyPLAN, which is specific for grid-based annual time-step analyses of the whole energy grid, including gas, electricity and heat [EnergyPLAN, 2018]. EnergyPLAN could very well be used as a model for the grid and perhaps future energy consumption, and the model includes distribution data for EVs, however there is little information as to where the authors obtained the distribution data, as well as where they obtained other distribution files, so therefore Excel was chosen instead because of the complete transparency in data gathering. Another model would be EnergyPRO, although this model is even less suited for the purposes due to it being a very localized model, intended for more in-depth analysis of smaller parts of the overall grid [EMD, 2018]. There are many other energy models on the market, but the ones mentioned were the most likely candidates, although they still did not live up to the requirements of this thesis.

Excel is not flawless however, it can often struggle with larger datasets, and especially when adding several calculated columns of data depending on other data points, which can slow Excel down considerably. Excel can at times be difficult to get to present the data in a meaningful way, meaning presenting data can at times be more time consuming than other models might be. Despite this, Excel stood out as the best choice for modelling the goals of this thesis.

4.8 The Math

To recap; The battery size of a given EV, is divided with the efficiency of the EV, further divided over the average annual driving distance for a danish citizen, which is then multiplied by the depth of discharge percentage, to establish what the range is, and how often the consumer is likely to need to refuel. Then, the EV amount in the given scenario is divided with the amount of days between recharges, and then distributed across a 24-hour cycle using the distribution data mentioned earlier, to attempt to calculate the amount of charging station visitors per hour. The amount of visitors is then divided over the hour depending on the charge speed - 30 minute vs 6 minute -, to figure out how many charge stations would be needed to cover demand, and this is in turn, multiplied by the charge speed of the given charge points, to figure out the peak MW consumption.

The math will be presented below in the order of performance, as in in which order the data was calculated, and therefore, it should be much easier to recreate the model, should the reader want to.

4.8.1 Transmission Grid Modelling:

- *a* = Battery size in kWh,
- *b* = Efficiency in kWh/100km
- *R* = Range in km
- *Ad* = Annual distance driven in km
- *DoD* = Depth of Discharge in %
- *Rs* = Refueling events per year
- *EVa* = Total amount of EVs
- *Dv* = Daily gas station visitors
- *Hv* = Hourly gas station visitors
- *Cs* = Charge speed
- *Cp* = Charge points

$$\frac{a}{b} * 100km = R \tag{4.1}$$

$$\frac{Ad}{R * DoD} = Rs \tag{4.2}$$

$$Rs * a * DoD = \text{Energy Demand} \tag{4.3}$$

$$\frac{EVa}{Rs} = Dv \tag{4.4}$$

$$\frac{Dv}{\text{Hourly distribution}} = Hv \tag{4.5}$$

$$\frac{Hv}{Cs \text{ in hours}} = Cp \tag{4.6}$$

$$Cp * \frac{Cs \text{ in kW}}{1000} = \text{Peak MW} \tag{4.7}$$

4.8.2 Distribution grid modelling:

- *EVa* = Total amount of EVs
- *Prc* = EV percentage of total vehicle amount
- *Tc* = Total consumption per hour
- *Rc* = Residential consumption per hour
- *Hc* = Household consumption per hour
- *Nt* = Test neighbourhood households
- *Nto* = Neighbourhood EV owners
- *Nc* = Test neighbourhood consumption
- *Lp* = Low-power home charging
- *Mp* = Mid-power home charging
- *Hp* = High-power home charging

$$EVa/\text{Total vehicle amount in Denmark} = Prc \tag{4.8}$$

$$Tc * 33\% = Rc \tag{4.9}$$

$$\frac{Rc}{\text{Total households in Denmark}} = Hc \tag{4.10}$$

$$Nt * Hc = Nc \tag{4.11}$$

$$Nt * Prc = Nto \tag{4.12}$$

$$Nto * Lp = \text{Low power home charging} \tag{4.13}$$

$$Nto * Mp = \text{Mid-power home charging} \tag{4.14}$$

$$Nto * Hp = \text{High-power home charging} \tag{4.15}$$

Scenario Analysis 5

This chapter will elaborate on the on the scenarios mentioned in Chapter 4 and 3: The 500K EV scenario, and the 2.5 million EV scenario. Also, a simplistic version of the distribution grid will be modelled as a contrast to the transmission grid. The distribution grid will be modelled according to what was mentioned in the methodology. Furthermore, there will be additional "extreme" fictional scenarios later in the report to further experiment with the model. The "fictional" part is due to the numbers used in those scenarios are made up by the author, and are not indicative of any real data.

As mentioned previously, in Table 4.2, three EVs will be used for increased modelling accuracy. The Renault Zoe, the BMW i3, and the Tesla P100D. The Renault Zoe has a battery of 42 kWh - although it has an optional smaller one - [Renault, 2018], and has an efficiency of 13.3 kWh/100km, according to the NEDC [NEDC, 2018]. The BMW i3 has a battery size of 94 Ah, and an efficiency of 12.6 kWh/100km, the NEDC also lists a range of 320km, and due to every other manufacturer listing their battery sizes in kWh, it is necessary to convert the 94 Ah to kWh, although this requires voltage information which is not listed, therefore it is calculated as a function of efficiency and range, which gives it roughly 40 kWh NEDC [2018]. Lastly, the Tesla P100D has a battery size of 100 kWh, and a range of 20.6 kWh/100km [Tesla, 2018; EPA, 2018]. This gives us three different vehicles to compare in the scenarios that have different efficiencies and battery sizes.

Each chart in this chapter shares the same formatting, therefore the different data series will be presented and explained here, furthermore, all the charts display MWh on the left axis, except for the distribution grid scenarios, where the displayed values are in kW. The "normal consumption" is the normal consumption of the hour, taken from 2017 data from [Energinet, 2018b]. The "Added Demand" is the expected demand added each day by the total amount of EVs, according to the calculations in the methodology. The "Grid Capacities" are the "ceilings" of the grid, as in what the grid can provide in total.

It should be noted here that the grid capacities only represent that maximum production capacity in Denmark, including import capacity, the source does not mention if the transmission grid is capable of transmitting all the power, and there was little data to be found around the maximum capacity of the transmission lines, therefore, the maximum production and import capacity is used instead. There are already projections that will be added by 2020, so these have also been included. A ceiling has been added for the grid capacity without intermittent energy sources, which means that is the ceiling which can be reliably provided, where the other ceilings include wind power, which by its very nature might not be available when needed. The non-intermittent ceiling is more likely to be the most useful ceiling due to it being reliable, whereas the wind-included ceilings could vary depending on weather at the time of peak hours, therefore it can be considered that the grid would be in trouble if the peak rises above the lowest line.

It would "only" take 167K owners to fast-charge at 100 kW simultaneously to go over the maximum current capacity with wind that the grid can handle and cause a nationwide blackout. 167K simultaneous visitors would only be 6.6% of the total amount of EV owners, in the full adoption scenario. Also, it would only take 121K concurrent visitors charging at 100 kW to break the lowest ceiling, undoubtedly causing some issues to the grid. This will be further elaborated in the coming sections.

5.1 Distribution Grid

In an attempt to model the impact on the distribution grids in Denmark, the example from [Spindler, 2014a] will be used as baseline, due to lack of data on distribution grid capacities and networks in Denmark. This means that the transformer capacity used in the model is taken from a rural area in Norway, and is therefore not necessarily representing the average distribution transformer in Denmark. The neighbourhood the norwegian transformer serves, is not necessarily similar to how an average danish neighbourhood might look. Through dividing the annual residential consumption with the amount of households in Denmark, a result of roughly 4500 kWh a year is given, which fits the published averages for household consumptions for 2017 [Gregersen, 2018]. This also means that the average hourly consumption for danish households is around 450 W, and in comparison with the test transformers capacity of 300 kW, the residential consumption is not significant at all. The original scenario did involve 11 commercial buildings as well, but as it was not possible to find useful numbers of commercial companies in Denmark that are connected to a distribution grid - instead of transmission - or the average consumption of these commercial entities, they were replaced in the test scenario by 11 additional households. On top of the 25 households and 25 cabins used in the norwegian scenario, it figures to 61 households on this "test grid", although the numbers have been calculated for a rounded down 60 households.

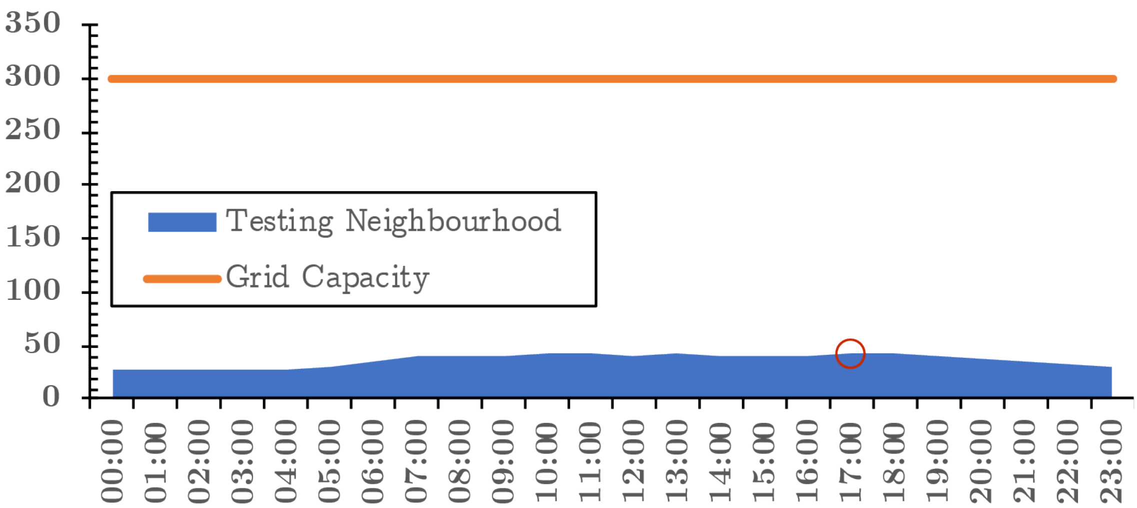


Figure 5.1: Normal Consumption

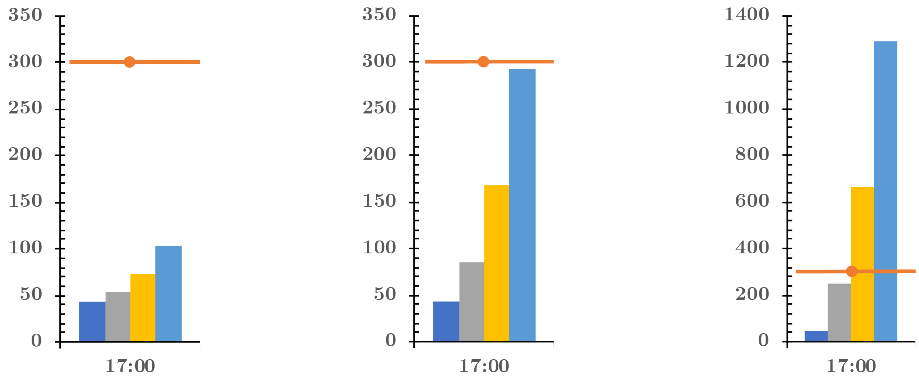
As mentioned in the methodology, consumption accuracy is increased through using a percentage statistic derived from dividing the scenario car amount - 500K - with the total amount of households in Denmark. The percentage is applied to the total amount of households in the testing scenario, to figure out how many households in that neighbourhood are likely to own an EV. Then, the common ways of home charging in Denmark are applied as consumption. 3.7 kW for normal home stations, 11 kW for "fast-charging", and 22 kW for the newest home chargers [Clever, 2018; E-ON, 2018]. This thesis does not necessarily assume that either one of the previously mentioned chargers would be in abundance compared to the others, but instead model them all individually. However, it is likely that EV owners would buy the fastest charger they can if it makes financial sense, especially when considering the vastly different charge times. There is no source for this particular piece of information, but instead a reflection of the authors belief that EV owners would gravitate towards the "most bang for the buck", and if the E-ON 22 kW chargers are decently priced, the EV owners would be more likely to buy it as it is considerably faster than the other options. This method should serve to showcase the potential impact of the EV scenario on the distribution grid to gauge if it might cause an issue.

It also seems as if the concentration of EVs is more important when attempting to figure out when the distribution grid will experience issues, concentration in this case meaning how many of the households in a given grid owns an EV, and at which speed they can charge. Due to this, the following charts show that even 500K EVs nationally do not necessarily indicate an issue for the average grid, but it doesn't take many more houses to own vehicles before the grid runs out of capacity. For this reason, a quick calculation can be made here, there is 300 kW available in the test grid, and the households barely have any impact as can be seen in Figure 5.1, therefore there is a good amount of space on top of the consumption for any EVs. Although at peak hours, it looks like there is around 250 kW left of capacity. 250 kW would only require 12 vehicles to break at 22 kW charging, 23 at 11 kW, and 68 at 3.7 kW. This indicates that no matter what, the grid is fine with 3.7 kW chargers, but will experience issues when enough residents install a dedicated charge point at 11 kW or above. Furthermore, there is a highlight in Figure 5.1, this is the peak that was mentioned earlier as happening around 17:00, although this peak does proceeed into the 18th hour as well. But that peak is the reason that Figures 5.2 are all display the 17th hour, as it seems to coincide with when owners come home from work, and would therefore be likely to plug their EVs in to their respective charge points.

Figure 5.2b shows that as a static entity, the EVs do not seem to cause an issue, however it should be noted that this is only with 11 out of the 60 households that own an EV, and there is room for "only" 50 kW of more consumption, if all the vehicles charge at 22 kW, which fits with the 12 vehicle breaking point mentioned earlier. However, if all owners stick to normal charging or 11 kW chargers, the issue does not present, and the distribution grid can handle many more vehicles before experiencing issues. This does indicate that with the adoption rate mentioned in the overall scenario, the average distribution grid should be fine. Also, further issues could potentially be mitigated through smarter charging or staggered charging so that not all vehicles charge at the same time.

In fact, it seems the local concentration of EVs will be the determining factor in whether or not a given transformer can handle the load, in which case it should not pose a significant issue for the local municipality or energy company to replace the specific transformers experiencing issues as the adoption penetration increases, relieving the need for smart charging systems in those neighbourhoods. Therefore it should be of interest to analyze different percentages instead of the specific scenario average, as the concentration of EVs is so important.

With 500K EVs, the statistical percentage of penetration is 19%, which amounts to roughly 11



(a) 120K EV scenario (b) 500K EV scenario (c) Full adoption scenario

Figure 5.2: Peak Results

households in the testing neighbourhood. The other scenarios mentioned in this thesis are 120K EVs, and full adoption, 2.5 million EVs. This means 4% and 100% penetration, respectively. 4% penetration causes even fewer issues for the distribution grid, as can be seen in Figure 5.2a, leaving a lot of room for additional EVs. However, at 100% penetration, the issues really present themselves, as can be seen in Figure 5.2c. The full adoption scenario causes very significant issues for the transformer in the test grid, even with 11 kW chargers. Even the normal charging doesn't have far to go before breaking the transformers capacity limit. The distribution grid will therefore need upgrading no matter what eventually, as the transformers will have to get very powerful before being able to handle such spikes in demand.

Overall, the distribution grid - as modelled - seems far stronger than necessary to supply the modelled demand. So it's highly likely that transformers used for normal neighbourhoods in Denmark are more load-fitting, and therefore comparatively weaker. What these charts show is that there is a limit to it all, and that high levels of EV concentration will likely cause issues for just about any transformer, as it seems unlikely there would be any distribution transformer strong enough to handle the peak seen in Figure 5.2c.

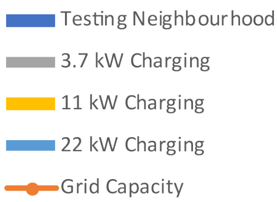
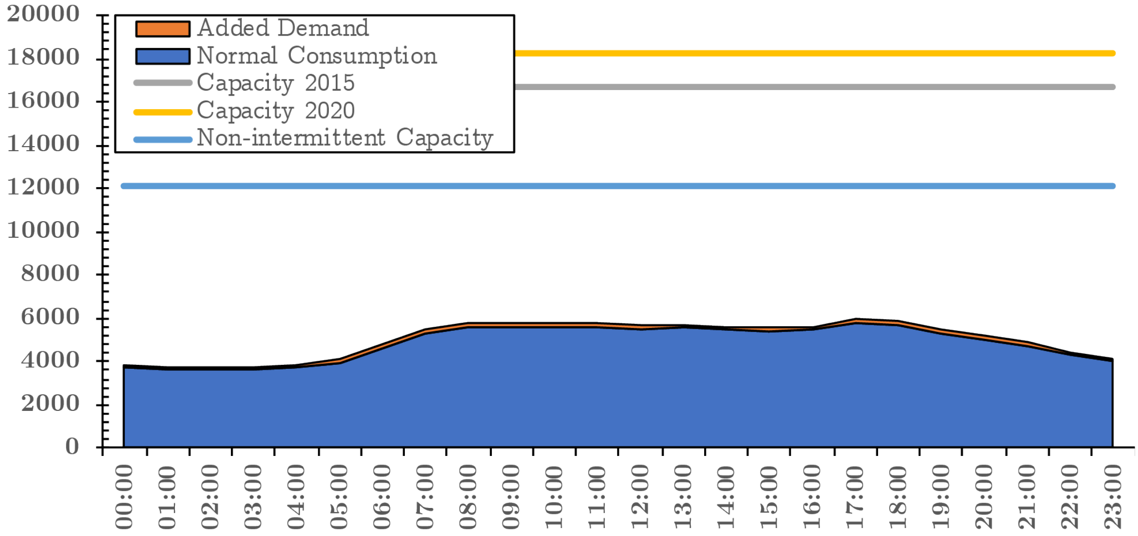


Figure 5.3: Distribution Chart Legend

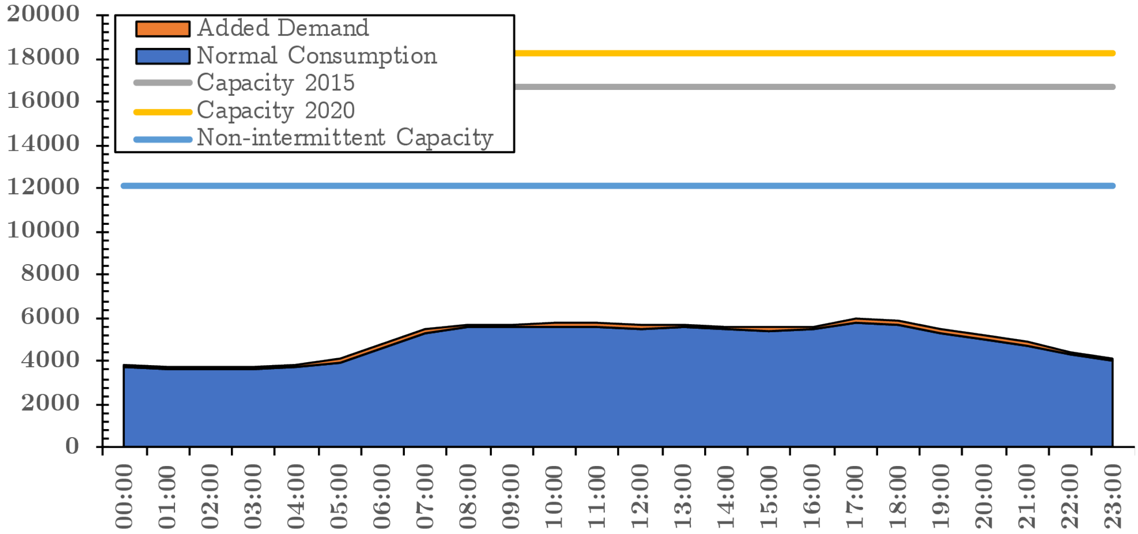
5.2 500K EVs; Transmission Grid

The first scenario modelled will be the older prognosis mentioned in [Malfelt, 2010] of 500K EVs. The choice was made as it was more extreme than the other scenario mentioned in the same article, and would therefore serve to illustrate the impact of EVs more than the other choice.

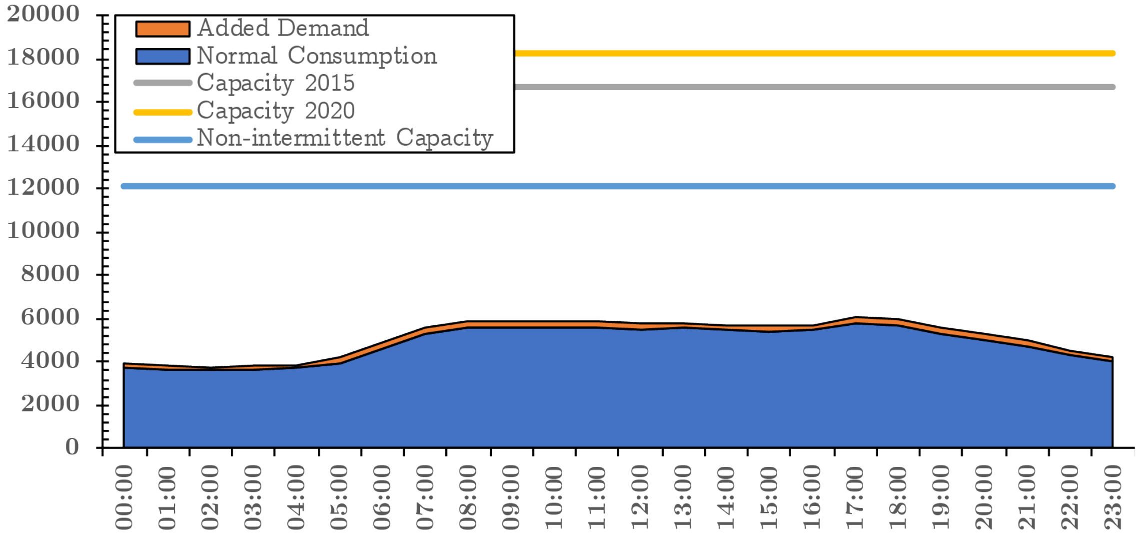
For reference purposes, a general peak consumption maximum has been observed at roughly 4500 MW on a given day [Energinet, 2018a], which will be relevant to understand the peak demands listed in this section, as well as the next.



(a) 500K Zoes



(b) 500K BMWs



(c) 500K Teslas

Figure 5.4: Scenario Results; Left axis is GWh, bottom represents hour of the day

5.2.1 Renault Zoe

First car modelled is the Renault Zoe, as mentioned previously, it has a battery size of 42 kWh and an efficiency of 13.3 kWh/100km, which is very respectable compared to competing EVs. When calculated and distributed according to the parameters mentioned in Chapter 4, the scenario does not look too bad for the transmission grid, as it barely adds any noticeable demand. Furthermore, the maximum grid capacity is inserted as a frame of reference as to when the grid would be overloaded, this capacity is taken from [Danish Energy Agency, 2014].

Figure 5.4a shows that the transmission grid barely takes any additional consumption in comparison with already existing consumption, which is further proven by the fact that the existing consumption models each worst hour in 2017 in terms of consumption, so even in comparison with the worst hours of consumption, the added load is not significant. This is also reflected in the amount of visitors per hour.

Table 5.2: 30 minute charge point visitors, at different SoC levels, Renault Zoe

	10%	**25%**	**50%**	**Peak MW 10%**	**Peak MW 25%**	**Peak MW 50%**	
Max	2,848.46	3,418.15	5,127.22	284.85	341.81	512.72	**MW**
Avg	2,008.23	2,409.87	3,614.81	200.82	240.99	361.48	**MW**
Min	999.46	1,199.35	1,799.03	99.95	119.94	179.90	**MW**

As expected in the methodology, the amount of hourly visitors to a given charging station changes with how long the average consumer is expected to wait before charging their vehicle, shows as "state of charge" percentage, as in what the battery indicator shows in the given vehicle. However, the hourly energy demand does not change, as the individual consumer charges fewer kWh per charge. Therefore this part of the analysis is mostly used to calculate how many visitors can be expected on an hourly basis, and through that, the absolute peak MW demand that can be expected from the scenario. Table 5.2 shows that if consumers charge at 50% SoC, then the peak hour will receive 5127 visitors, which results in a peak demand of 512 MW. This is, in comparison to normal consumption, not a significant problem. The daily max hovers around 4500 MW on a national basis, which means the 512 MW would be an 11% increase. The scenario does show however, that there would be at least a minimum of 99 MW added, as well as at least 1000 visitors per hour. With faster available charging, it is possible to expect fewer simultaneous visitors to a given station as it takes a shorter time to charge the vehicle. Therefore Table 5.3 reflects this, and at peak hours, there will be at worst 1025 visitors, causing a 358 MW peak, and a constant 199 visitors, demanding 69 MW.

Table 5.3: 6 minute charge point visitors, at different SoC levels, Renault Zoe

	10%	**25%**	**50%**	**Peak MW 10%**	**Peak MW 25%**	**Peak MW 50%**	
Max	569.69	683.63	1,025.44	199.39	239.27	358.91	**MW**
Avg	401.65	481.97	722.96	140.58	168.69	253.04	**MW**
Min	199.89	239.87	359.81	69.96	83.95	125.93	**MW**

5.2.2 BMW i3

The BMW i3 is very similar to the Zoe in both maximum battery capacity as well as efficiency, being slightly more efficient, but also slightly smaller battery, which results in roughly the same range, and therefore also very similar hourly visitors and MW demand. But due to being the second most popular EV in Denmark, it will be modelled for comparison. Another EV could have been chosen, but most EVs currently on the market are fairly similar, aside from the Tesla P100D that will be analyzed later.

As with the Renault Zoe, the total energy demand impact is not significant, barely enough to display on Figure 5.4b in comparison to normal consumption, and especially in comparison to the overall maximum grid capacity.

Table 5.4: 30 minute charge point visitors, BMW i3

	10%	**25%**	**50%**	**Peak MW 10%**	**Peak MW 25%**	**Peak MW 50%**	
Max	2,833.46	3,400.16	5,100.24	283.35	340.02	510.02	**MW**
Avg	1,997.66	2,397.19	3,595.79	199.77	239.72	359.58	**MW**
Min	994.20	1,193.04	1,789.56	99.42	119.30	178.96	**MW**

Furthermore, as expected, the differences between the i3 and the Zoe in terms of hourly visitors is not significant, as shown in Table 5.4 and 5.5. Peak visitor count is at 5100, versus 5127 mentioned in Table 5.2, and a peak demand of 510 MW versus 512 MW with Zoes. In either case, these vehicles do not pose a significant threat to the grid, even at 500K.

Table 5.5: 6 minute charge point visitors, BMW i3

	10%	**25%**	**50%**	**Peak MW 10%**	**Peak MW 25%**	**Peak MW 50%**	
Max	566.69	680.03	1,020.05	198.34	238.01	357.02	**MW**
Avg	399.53	479.44	719.16	139.84	167.80	251.71	**MW**
Min	198.84	238.61	357.91	69.59	83.51	125.27	**MW**

5.2.3 Tesla P100D

Due to picking the top model version of the other two vehicles for comparison, the current top model of Tesla is picked too. With a battery of 100 kWh, and an efficiency of around 20 kWh/100km, makes it the least efficient of the modelled vehicles, but also the one with the largest battery. The large battery significantly outweighs its lower efficiency in terms of driving range, and it is therefore also the one with the fewest visitors per hour due to the distance it can drive on a single charge.

Despite the lower efficiency, the power demand added by the Teslas is not that significant on an annual scale, it is more pronounced than the added demand of the other two EVs, but it is still not very significant in comparison to the maximum capacity of the grid, which further proves that the danish transmission grid is very strong, and can handle far large dips and peaks than can be realistically created. As Figure 5.4c shows, the added demand is a bit more visible than in the earlier figures, but is still small enough to not be noticeably visible. The Zoe adds around 1.4

TWh annually to the power demand, the i3 adds a very similar 1.3 TWh, and the Teslas add a total of 2 TWh of demand on top of the normal annual demand of 33 TWh.

As for the hourly visitors, it is noticeably lower than the other two EVs, due to the fact that the Teslas - despite lower efficiency - have considerably longer driving ranges than the others, and therefore, with average driving distance per year, they have to recharge less often. A maximum of 3319 hourly visitors can therefore be expected with Teslas, if the consumers charge at 50%, with a peak demand of 331 MW. In comparison to the roughly 500 MW of the previous vehicles, this is a noticeable drop. Furthermore, the minimum expected visitors is 647, with a demand of 64 MW, as can all be seen in Table 5.6.

Lastly, in Table 5.7, a peak visitor count of 663 and peak demand of 232 MW, shows that the realistic impact of these vehicles charging is not significant enough to cause any kind of concern.

Table 5.6: 30 minute charge point visitors, Tesla

	10%	**25%**	**50%**	**Peak MW 10%**	**Peak MW 25%**	**Peak MW 50%**	
Max	1,844.00	2,212.80	3,319.20	184.40	221.28	331.92	**MW**
Avg	1,300.06	1,560.08	2,340.11	130.01	156.01	234.01	**MW**
Min	647.02	776.42	1,164.63	64.70	77.64	116.46	**MW**

Table 5.7: 6 minute charge point visitors, Tesla

	10%	**25%**	**50%**	**Peak MW 10%**	**Peak MW 25%**	**Peak MW 50%**	
Max	368.80	442.56	663.84	129.08	154.90	232.34	**MW**
Avg	260.01	312.02	468.02	91.00	109.21	163.81	**MW**
Min	129.40	155.28	232.93	45.29	54.35	81.52	**MW**

5.2.4 Sum-up

When compared with the results in the distribution grid scenarios from earlier, the transmission grid seems much more capable at handling the 500K vehicles of this scenario. The determining factors for the transmission grid seems to be timing of demand, as in when consumers want to charge, and therefore how many concurrent chargers there are at any given moment. The total demand is not a problem, nor is the demand with the distribution used in this model. However, for reiterative purposes, "only" 167K vehicles have to concurrently charge at 100 kW to cause a problem, and only roughly 55K vehicles at 350 kW, so with 500K vehicles on the road, it is theoretically possible for this scenario to break the grid, but it would have to be a "freak occurence", one such as this will be mentioned in the Discussion later on. In short, the Teslas with the bigger batteries and lower range means that the annual demand is higher than the other vehicles but concurrent visitor count is lower, and as was mentioned, the concurrent visitor count is far more important to grid stability than total demand, therefore the Teslas offer a safer option for the grid than the other two vehicles. Although this doesn't mean that much when compared to the ceilings of the grid in either case, because neither vehicle poses any threat to the grid, so while the Tesla is technically better, the other two vehicles are not likely to be causing any issue regardless.

5.3 Full adoption

The final scenario to be modelled on the transmission grid is if / when all vehicles in Denmark become electric. There are currently roughly 2.5 million personal transportation vehicles on the danish roads. If all of those became electric, it would add their total electricity demand to the grid. This scenario is expected to stress the model that was made, and to test the model sensitivity. 2.5 million cars is not unrealistic in and of itself, as Denmark is steadily moving away from fossil vehicles, and therefore it can be expected that at some unknown point in the future, there will be few - if any - fossil cars left on the roads. This thesis will not attempt to figure out a timeline for this transition, but will instead try and model what might happen to the grid if this transition happened a lot faster than expected.

5.3.1 Renault Zoes

Figure 5.5a shows that in comparison to Figures 5.4a and 5.4b, the demand impact of full EV adoption worth of Renault Zoes is far more noticeable, however in comparison to the maximum grid capacity, it is still not a cause for concern. This is in large part due to the distribution of consumption, while there are indeed many vehicles to power, the assumption that the owners would only charge when they had to, makes the power demand much easier to supply. Issues might be more pronounced if owners charged indiscriminately. The Zoes would add an annual demand of 7.3 TWh, which means it would add 22% more demand on top of the already existing 33 TWh demand.

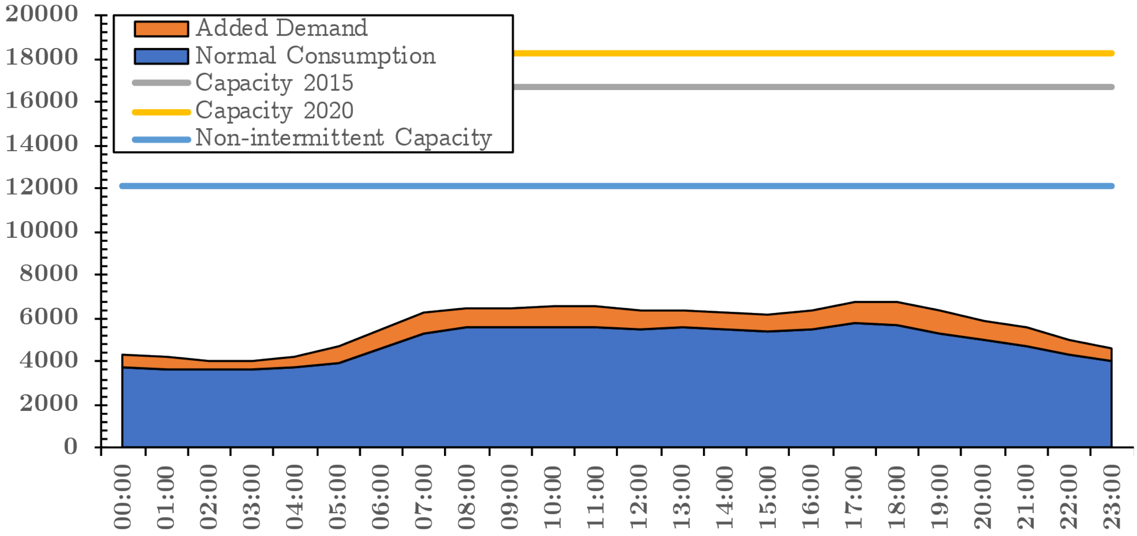
As for visitor count, they are understandably significantly increased, as the amount of EVs is equally significantly increased. And here we will see that peak demand might give some cause for concern. Table 5.8 and 5.9 show that at maximum expected peak, there will be 28,200 visitors, causing a 2820 MW peak demand, and when taken in comparison to normal consumption peak demand of 4200 MW, it adds a significant 67% addition to peak demand. While it is still not getting close to the 16.7 GW peak that the transmission grid can provide, it should still be a cause for careful planning to handle such large peaks. Furthermore, this model assumes rather neat and perfect owner behaviour, the behaviours will not have to deviate significantly to really start to stress the grid.

As for the minimum demand, Table 5.8 shows an hourly minimum of 5500 visitors, and with it, 550 MW of constant minimum demand. This is interesting in relation to the previous results for the 500K scenario, where the Zoes and i3 peaked at 512 MW on the worst hours. So in short, the minimum added demand in this scenario supersedes the maximum demand added in the 500K EV scenario.

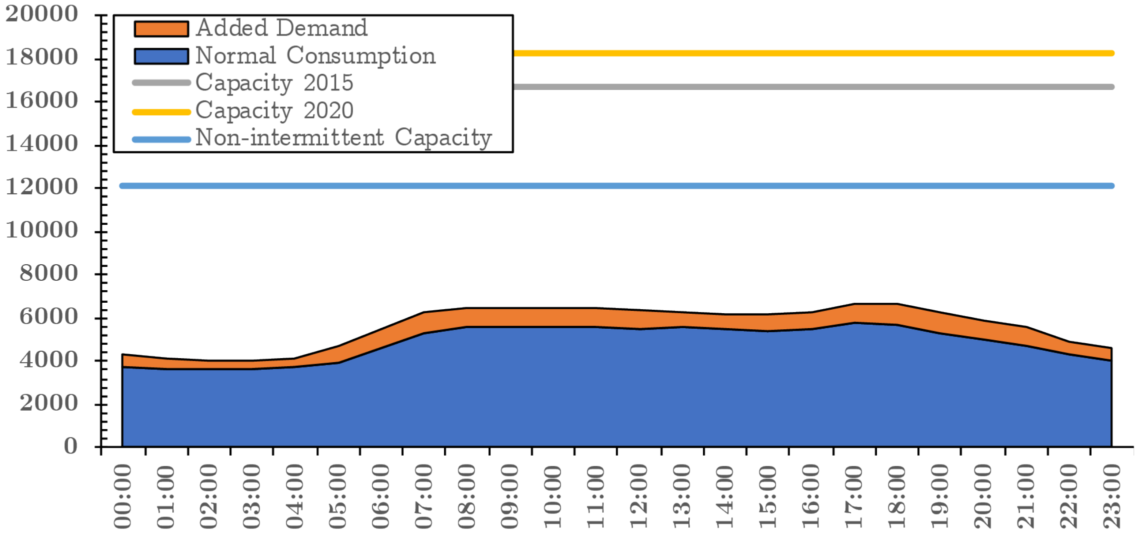
The 6 minute table shows similar results, a peak visitor count of 5640 visitors, causing a peak demand of 1973 MW, and a minimum visitor count of 1100 and a constant demand of 385 MW. Just like the other results the 6 minute charge points would not necessarily attract as many simultaneous consumers as the 30 minute ones due to each consumer having to stay for shorter periods of time.

5.3.2 BMW i3

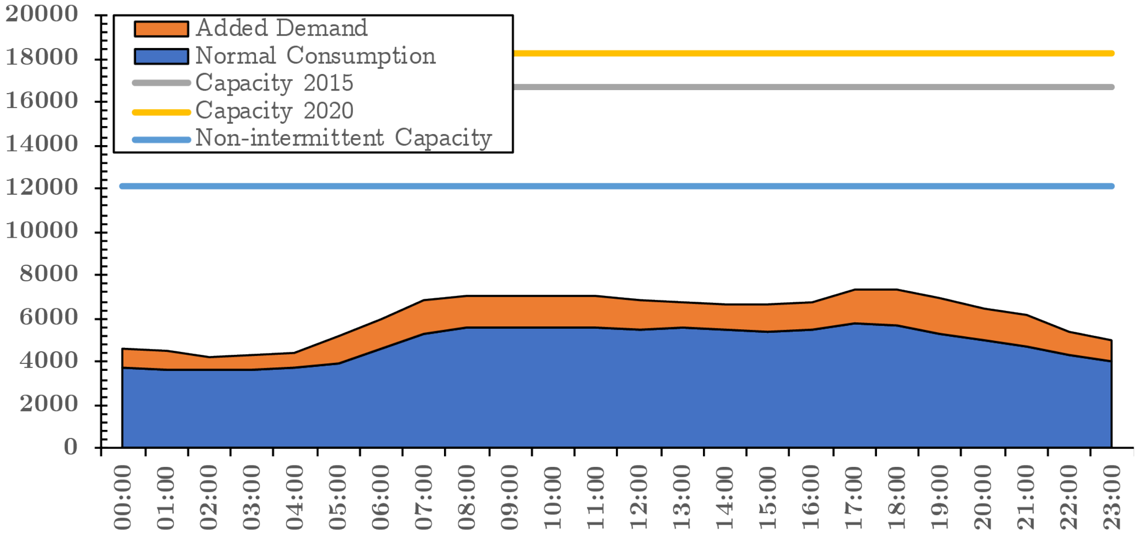
In the previous scenario, the i3 and the Zoe were very closely matched, due to similar battery sizes and efficiencies, and this similarity continues in the full adoption scenario, although the real



(a) Full Zoes



(b) Full BMWs



(c) Full Teslas

Figure 5.5: Scenario Results; Left axis is GWh, bottom represents hour of the day

Table 5.8: 30 minute charge point visitors, Zoes

	10%	25%	50%	Peak MW 10%	Peak MW 25%	Peak MW 50%	
Max	15,666.51	18,799.81	28,199.72	1,566.65	1,879.98	2,819.97	**MW**
Avg	11,045.26	13,254.31	19,881.46	1,104.53	1,325.43	1,988.15	**MW**
Min	5,497.02	6,596.43	9,894.64	549.70	659.64	989.46	**MW**

Table 5.9: 6 minute charge point visitors, Zoes

	10%	25%	50%	Peak MW 10%	Peak MW 25%	Peak MW 50%	
Max	3,133.30	3,759.96	5,639.94	1,096.66	1,315.99	1,973.98	**MW**
Avg	2,209.05	2,650.86	3,976.29	773.17	927.80	1,391.70	**MW**
Min	1,099.40	1,319.29	1,978.93	384.79	461.75	692.62	**MW**

number gap between the two models increases. Notably in the added demand, where the Zoes would add 7.3 TWh annually, the i3s would add 6.9 TWh, which is a difference of 400 GWh. On a national scale it is not that significant but it still represents a fairly large difference. In any case, the total demand impact is equal in severity to the Zoes, with the 6.9 TWh adding 21% more demand to the total demand, whereas the Zoes would add 22%. The difference between the two are even less apparent in the hourly visitor count. The i3 visitors would peak at 28,000, where the Zoes would peak at 28,200, and therefore the added peak demand is very similar, 2800 MW vs 2820 MW respectively. As mentioned with the Zoes, this is a fairly significant demand increase compared to normal consumption.

The minimum added demand is very similar to the Zoes, so much so that there is little reason to highlight them here. Instead it should be noted that the two top EVs in Denmark in terms of purchases are so similar that if the future were to consist of largely these two, then the grid would not experience significant issues, and could easily handle the full demand of a total conversion to electric power.

Table 5.10: 30 minute charge point visitors, BMW i3

	10%	25%	50%	Peak MW 10%	Peak MW 25%	Peak MW 50%	
Max	15,584.06	18,700.87	28,051.30	1,558.41	1,870.09	2,805.13	**MW**
Avg	10,987.12	13,184.55	19,776.82	1,098.71	1,318.45	1,977.68	**MW**
Min	5,468.09	6,561.71	9,842.56	546.81	656.17	984.26	**MW**

Table 5.11: 6 minute charge point visitors, BMW i3

	10%	25%	50%	Peak MW 10%	Peak MW 25%	Peak MW 50%	
Max	3,116.81	3,740.17	5,610.26	1,090.88	1,309.06	1,963.59	**MW**
Avg	2,197.42	2,636.91	3,955.36	769.10	922.92	1,384.38	**MW**
Min	1,093.62	1,312.34	1,968.51	382.77	459.32	688.98	**MW**

5.3.3 Tesla P100D

The Teslas are - as expected - the ones to add the largest amount of demand to the grid, being the least efficient of the vehicles tested. A full conversion to Tesla-type vehicles would add 11.3 TWh of annual demand, which is a a roughly 34% increase. However, due to their very large batteries and therefore very long range, they don't need to recharge as often - given average driving patterns - and therefore won't cause as significant peaks in demand as the other cars modelled. Therefore, depending on the EVs in question, either there will be a large annual demand added due to low efficiency, or high peak demand added due to low battery size, so far it seems as if large batteries carry an efficiency penalty, but this is not necessarily indicative of future EVs, although it makes logical sense that the bigger the battery, the heavier the vehicle, and therefore the lower the efficiency. In either case, the danish transmission grid can handle a very significant amount of added demand - both peak and annual - before experiencing issues, and since expansion of the grid is already planned, it is unlikely that Denmark will experience similar problems as Norway, if Denmark manages to make centralized charging more beneficial to consumers than home-charging.

Tables 5.12 and 5.13 show that compared to the Zoes and i3s, the maximum hourly visitor count is lower, and therefore the peak demand is equally lower as well. While it is true that the Teslas would need to charge more kWh at the same time than the Zoes, due to li-ion batteries only being able to fast-charge to a certain percentage, at which point most batteries charge at the same rate [Battery University, 2018a], the time they take at each charging point will likely be somewhat equal, although the peak demand might change to reflect the lower power at the end of the fast-charging cycle. This thesis argues that given equal charge speed potentials - as in the equal peak charge rate - the vehicles would cause the same peak demand, but the smaller battery vehicles would shorten the time this peak demand would continue.

Table 5.12: 30 minute charge point visitors, Tesla

	10%	**25%**	**50%**	**Peak MW 10%**	**Peak MW 25%**	**Peak MW 50%**	
Max	10,191.48	12,229.77	18,344.66	1,019.15	1,222.98	1,834.47	**MW**
Avg	7,185.23	8,622.28	12,933.41	718.52	862.23	1,293.34	**MW**
Min	3,575.96	4,291.15	6,436.72	357.60	429.11	643.67	**MW**

Table 5.13: 6 minute charge point visitors, Tesla

	10%	**25%**	**50%**	**Peak MW 10%**	**Peak MW 25%**	**Peak MW 50%**	
Max	2,038.30	2,445.95	3,668.93	713.40	856.08	1,284.13	**MW**
Avg	1,437.05	1,724.46	2,586.68	502.97	603.56	905.34	**MW**
Min	715.19	858.23	1,287.34	250.32	300.38	450.57	**MW**

5.4 Sum-up

The danish transmission grid is very strong, and it seems that even if every single personal transportation vehicle is converted to electric, it would still not cause any significant issues for the grid, although this is assuming efficient distribution of power demand. As mentioned earlier, it would only require 167K vehicles to start charging at the same time to cause a nationwide blackout, the likelihood of that happening is low due to the chance of that amount of vehicles needing - and being able to - charge at the same time. It would seem that the worst peak is caused by Zoes, with 28,200 concurrent visitors, which is a far cry away from the 167K previously mentioned. The 28,200 also only represent 1.12% of the total amount of vehicles. For this reason, a fictional extreme scenario will be presented in the Discussion to expand upon the previous statement that the grid is particularly strong, to see if it is possible to "break" it.

Discussion 6

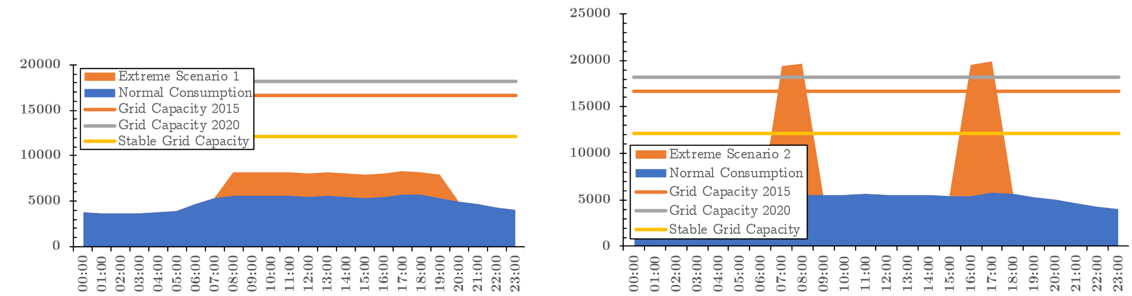
The discussion will be split into two parts, one part covering two fictional "freak occurrence" scenarios, where the owners of Teslas in the full adoption scenario from the analysis suddenly decide to behave erratically, such as only charging in the daytime, or only charging before and after work. The second part consists of a discussion of the method itself, the model and the results.

6.1 Part 1: Fictional Extreme Scenario

While it may seem as if the analysis proved slightly fruitless, due to the transmission grid seemingly being strong enough to handle even full electrification, it only requires a "freak occurence" to start causing some issues. As an example, Figure 6.1a shows what the grid would look like if the same amount of people in the full adoption scenario of Teslas only charge during the day in equal amounts. Which apparently still is not an issue, the peak demand added by the vehicles is an issue though, as can be seen in 6.2a, although only if charging at 350 kW. Then, Figure 6.1b shows what would happen if owners only ever charge before and after work, condensing all demand into two hours of the day. This is naturally not something that is likely to ever happen, but it shows that it doesn't take much before the grid might be overloaded, and as it shows, the demand breaks through all 3 ceilings, which means that the demand would be completely impossible to cover by the transmission grid, as the ceilings include import and every generator attached to the grid, now and expected in the future.

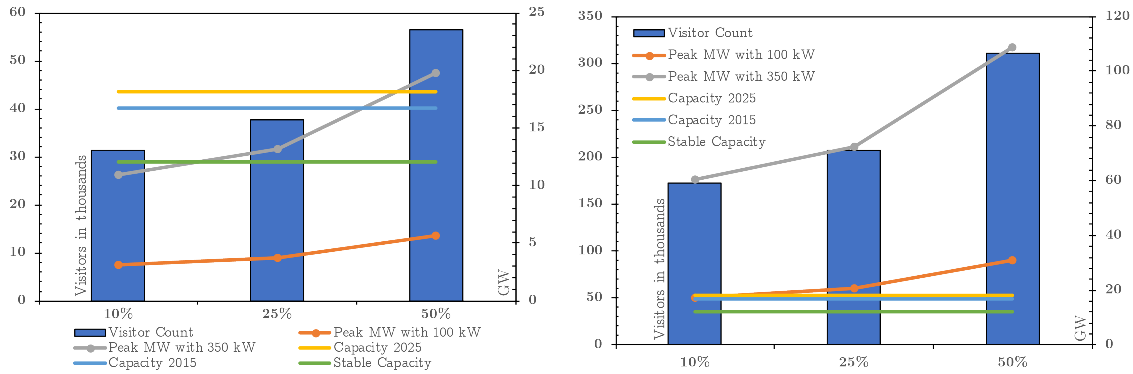
To further cement this issue, Figure 6.2a and 6.2b shows the peak demand. The straight lines represent the maximum grid capacity, and in Figure 6.2b, the demand shatters the ceiling, both with 100 kW chargers as well as 350 kW ones. Figure 6.2a shows that 350 kW chargers could regularly break the ceiling in the daytime only scenario. In the case of the daytime only charging, if the consecutive visitor count breaks 30K on 350 kW chargers, the demand will have broken through the lowest ceiling, the one that indicates "stable capacity", as in capacity that is not intermittent, so without wind. If the visitor count goes over around 45K on the 350 kW chargers, the demand will have broken through all ceilings of the grid, and would cause a nationwide blackout. Furthermore, as mentioned in the analysis, the concentration of EVs is key to managing the demand, if the concentration of EVs charging at any given time is too high, then the grid cannot cope, therefore it should be considered to put in regulation to limit that from happening, such as a national limit on charge point amounts, or at least how many charge points can be active at any given minute.

There is not much else to add on top of this scenario, other than it simply serves to show that the same amount of vehicles distributed differently makes all the difference in terms of grid stability. This should perhaps mean that the government should impose rules for how many charge points can be installed in total and / or how many can be active at any given time, as a security measure. It is - as mentioned - very unlikely that this will ever happen, but it is nonetheless a situation that could cause significant damage to the grid and anything connected to it, and should therefore be avoided as much as possible. With that said, the personal transportation sector does not seem to be able to cause trouble for the transmission grid, and it might perhaps be other factors that should be considered instead, such as financing, and added demand from other sectors "coming online" so to speak, electrified. A future example could be added commercial transportation, which this model is also fully capable of, and that might perhaps cause more issues.



(a) Daytime Charging (b) Two-hour Dharging

Figure 6.1: Extreme scenarios demand charts; GWh on the left



(a) Daytime only visitors (b) Two-hour visitors

Figure 6.2: Extreme scenarios visitor counts and impacts

6.2 Part 2: The method, model and results

One of the problems with the model used in this thesis is the amount of extrapolation and therefore potential inaccuracies that might appear due to this. As mentioned before, the future is not easy to predict, and it happens often that the future is over or underestimated. Due to having to use current data to try and predict how the future will pan out, it leaves out the potential of future changes. One example is EVs, they're currently in a very early stage - if one ignores the ones that came out in the 60's - and have yet to reach their true potential in terms of range, efficiency, and production speed. Currently, it seems as if many major car companies are aiming for a 2020 release of entirely new EV model lines [Matousek, 2018]. These upcoming EVs do not have many specifications released, and it is therefore not possible to model them using this model, just yet. The behavior of the EV drivers in the model is further extrapolated from behavioural data from fossil car drivers in other countries, and therefore does not - and cannot - reflect the actual behaviour of Danish drivers, although in this case it should be noted that the countries that the data comes from, are in many ways considered similar to Denmark [Zhang et al., 2015; Spoelstra, 2014; Turrentine et al., 2011].

However the model supports any configuration of vehicle battery size and efficiency, and once those numbers become available, it is easy to add them. Furthermore, the data on consumption are based on the full year of 2017, in terms of electricity consumption in Denmark. There has been made no attempt to try to extrapolate data from this consumption data towards the future, but it is unlikely that the consumption will stay static. This data can in turn be easily added once available, as well as many of the other data points, such as charging speeds, annual driving distance and others can be easily modified or added to as more data becomes available, ever increasing the accuracy of this model. While it cannot be used for implementation purposes, it serves to generate a good overview of the electricity grid, and what would happen if certain amounts of demand was added, as well as when this demand would be likely to peak. As an example of future expansion, Denmark is yet to reach the "foot of the mountain" in the market adoption curve, so it is entirely possible that within the next few years, there will be a large increase in EV purchases, as reflected by the market adoption curve in [Straub, 2009].

The charging stations in question are based mostly on current fast chargers, but also on already-built and upcoming ultra-fast chargers. The speed of the chargers will also heavily impact how many consumers can be served at the same time, as well as how high the peak demand will be. On that note, it should be mentioned that the 350 kW chargers have been marked as "6 minute charge points", but in reality this is unlikely to be the real speed, as the "6 minute" figure is based upon the Toshiba battery article, and as mentioned in the methodology, is not necessarily indicative of how fast the 350 kW stations could potentially charge. However, there is no information on how fast they expect these 350 kW chargers to be able to charge a given vehicle, and when the fact about how li-ion batteries fast charge are kept in mind, it is difficult to give an accurate estimate as to how long it would take the average vehicle to charge. Although it could perhaps be extrapolated in terms of how fast the vehicles charge now with 100 kW chargers, and then just divided by 3.5, but this would add some aspects to the different scenarios that were perhaps unnecessary to illustrate the overall point. This increase in accuracy could be used at a later date to enhance the model accuracy.

The transmission grid is so strong that it is not likely to experience any significant issues, at least according to the parameters with which it was tested, and only the previously explored "freak occurrences" are likely to cause any issues. The distribution grid is strong as well, although the fairly inaccurate method of modelling may have skewered the results slightly. Even so, it seems that if the DSO is adequately warned in advance of any larger increase in EV population in the respective areas, it should not be a technical issue to upgrade the necessary transformers to supply the energy. One thing that came up near the end of the writing of this thesis, was the posited issue of residents living in rental situations, like apartment blocks, not being able to buy and set up home charge points, and will therefore need access to centralized charging stations [McDonald, 2018]. This could be interesting to pursue further, as an argument in favor of centralized charge stations, simply due to the low accessibility for rental residents to buy and set up home charging stations.

Finances could further improve the accuracy of the model, as that could perhaps modify the scenarios in favor of either grid, due to potential price differences between setting up centralized stations vs home-charging. As the previously mentioned article considers, the population living in rented living might not be able to set up a home-charging station and therefore might rely on central stations for their recharging needs, this could in turn also impact the model outcome.

Choice Awareness guided this thesis towards its goal, even if there was no apparent real choice to make, as it seems either grid works fine with the transmission grid being slightly ahead when really extreme vehicle amounts are considered. In the vein of the choice awareness theory, the choices between the two grids were posited as potential solutions to a potential future problem on charging EVs. Without a clear choice, more factors may have to be considered to define the choices further, and to set them up in a way that defines the choices in a better way.

Conclusion 7

Before this chapter properly begins, the problem formulation should be reiterated, so that it can be concluded on;

"How will EVs impact the future electricity grid, and what is the most efficient way to deal with it?"

To help triangulate the issue, these sub-questions will be used;

- What would the grid look like with different amounts of EVs?
- How many EVs will "break" the grid?
- Is the transmission grid better than the distribution grid for EV charging?

For the purpose of clarity, each question starting from the bottom-up, and therefore finishing with the main problem, will be answered according to the methods presented in the methodology.

7.1 "Is the transmission grid better than the distribution grid for EV charging?

It turns out, that the distribution grid itself is fairly strong, and given normal statistical concentration of vehicles in each neighbourhood, even 500K vehicles on the road will not cause significant issues for the distribution grid as it was modelled. Although, it was mentioned in the analysis that the distribution grid was modelled based on a rural example from Norway, and not necessarily indicative of how the distribution grid is laid out in Denmark, much less so in urban areas. However, due to lack of good data on the topic, the Norway example was considered accurate enough to give an impression. In any case, if the relevant DSO's are warned in advance of large-volume EV purchases under their purview, they can strengthen the distribution grid as necessary, and it was proven in the analysis too, that the transmission grid will have no trouble with significant amounts of EVs on the road. The power is not lacking, perhaps only the delivery methods have issues, and those can be rectified as necessary. DSO's should however, be aware that this might be an actual problem if they are not made aware in advance if a given neighbourhood buys a large amount of EVs.

Specifically, the distribution network could start experiencing issues if enough residents install 22 kW chargers. In the 500K scenario, the 22 kW bar reaches just below the transformer ceiling. But if the lack of proper consumption data is considered, that spike could be breaking through the ceiling fairly easily, as it only leaves around 50 kW of demand space left for that particular neighbourhood. With more accurate data, the distribution grid scenario could significantly change in either direction. It seems more likely that the same strength transformer would serve more demand than what was modelled, as it seems like an oddly strong transformer for such a low demand. The most significant issues for distribution grids seem to be the concentration of EVs. As in how many EVs are concentrated in a given neighbourhood, and how fast they are capable of charging.

7.2 "How many EVs will "break" the grid?"

The current maximum capacity of the danish transmission grid is 16.7 GW, slated to be expanded to over 18 GW by 2025. This means that very simple math would show that 167K vehicles charging at 100 kW simultaneously will break it. What does this mean then? Well, 167K is a lot of vehicles in comparison to 500K overall vehicles, but when that number rises to full penetration, 2.5 million, then 167K vehicles is "only" 4%, so perhaps it is possible that the transmission grid might experience issues, or be severely stressed, at that point in time. with the additional 1.3 GW added, it raises that ceiling a bit. However, with the normal distribution used in this thesis, that ceiling is very, very far off. It was, however, mentioned in the analysis that perhaps the ceiling of 16.7 GW wouldn't be truly representative of the grid's capacity, as that ceiling includes wind power, which is inherently intermittent. Furthermore, the source for the capacity data did not indicate if the transmission grid itself could handle all the power available.

Although it should be noted that the above example was made with 100 kW charging in mind. If the new ultra-fast chargers were the only available chargers, at 350 kW, it would mean 48K concurrent chargers would be enough to break the grid. At just 28.7% of the 167K previously mentioned, and just 1.9% of the full scenario, it seems more likely to happen. But again, because of the faster charging available, the concurrent visitor count is significantly lower than in the other charge points, due to how fast they are able to charge. So it would seem even more unlikely to happen, as the visitors would only need to wait around 6 minutes to get a spot, and therefore all those 48K vehicles would have to start charging at the *exact* same time to cause problems. The ceiling without wind is 12.1 GW, which in turn means that only 121K owners need to charge at 100 kW to break it, or 35K at 350 kW. Which would be 4.8% and 1.4% respectively. So in short, there is the possibility that the grid could experience severe stress in heavy-traffic periods, but overall it seems that the danish grid can handle full personal electrification just fine.

7.3 "What would the grid look like with different amounts of EVs?"

As this thesis progressed, it became apparent that even the most extreme prognosis, wasn't as big an issue if it was distributed correctly. Therefore the scenarios boiled down to just 500K, and the full electrification, both of which proved that normal distribution is such a solid method that the grid is unlikely to experience anything but perhaps intermittent issues. However these grids were visualized, and estimates were made on the maximum concurrent visitors in each case, and how that might impact the grid in terms of power demand.

7.4 "How will EVs impact the future electricity grid, and what is the most efficient way to deal with it?"

This question fed into the theory of Choice Awareness, and the goal was to present two - or more - distinctly different ways to serve the power demand created by the rise in EVs. By posing the choice between a distribution grid approach and transmission grid approach, it seems as if either choice is just fine, and perhaps a mix of both might be the most preferable scenario, and in that case the most likely one. If either grid can handle the stress, it would seem apparent that there is no need for a choice, and that the grid can fairly easily respond to the increase in EVs, as long as it isn't so drastic that the DSO's cannot expand the distribution grids fast enough.

That being said, perhaps the choice is not on which grid is the best suited to provide the power, but instead in how to get that many vehicles on the road. As mentioned previously, currently Denmark only has 9,111 EVs on the road, and it seems as if 500K - let alone 2.5 million - is very very far away, and it might not even be an actual issue until much later than anticipated. Simply put, Denmark is not going to have an issue providing the power for the vehicles, but instead it will have issues getting the vehicles in the first place. This is a topic for another thesis entirely, but in terms of power demand, Denmark is doing fine.

7.5 The Choices

So to sum up; Denmark is not going to have an issue providing the power for any realistic amount of EVs, and it seems as if only "freak occurrences" is likely to cause noticeable issues for the grid itself. Therefore there does not seem to be an actual choice to make here, but instead the focus should be on how to get that many EVs on the road at all. It simply seems as if either grid works just fine, and the above mentioned "freak occurrences" are very unlikely to ever happen, which is why this thesis concludes with the statement that as far as the research shows, the distribution grid is strong enough to handle a significant increase in EV penetration, and should be expandable before reaching a critical point, and the transmission grid is so strong that it would take a very large "freak occurrence" to cause any issues for it, as was shown in the Discussion. It could therefore be concluded that this thesis does not adequately offer any choices, as there is no apparently *technical* reason to take any specific action. The reason that it's presented this way, is because there is the possibility that once economics are included, the choices may change, this was beyond the scope of this thesis, but this does not mean that it is not an area that could need further exploration.

Reflections 8

This chapter will be written as my experiences while writing this thesis, it is not meant for publication in itself. During the process of writing this thesis, I realized a lot of things. At first I started out wanting to explore if it was possible - and feasible - to stabilize consumption, through various kinds of storage. However it turned out that the demand does not peak or dip enough to make any kind of stabilization really matter, especially not when compared to pricing. The goal then was to stabilize consumption in anticipation of the rise of electric vehicles. I then moved on to try to illustrate what would eventually happen to the grid if a significant amount of EVs were added, and I was expecting 500K EVs to cause a lot of problems, so I had lined smaller scenarios up as well, and wanted to start with the extreme and move down to a more reasonable level. But as it turned out, 500K is not an issue at all, unless drivers behave erratically. That meant I had to cut the smaller scenarios as it no longer really made any sense to model them, if 500K provided no problems. So instead I looked into full electrification, expecting that to *definitely* break something, but then it didn't. As it turns out, the danish electricity grid is much stronger than I had anticipated, so much so, that even full electrification of the private sector provides no problem, again unless drivers behave erratically. Although it is possible that if all transportation, commercial included, was converted to pure electricity, *then* it might cause a problem, but that was beyond the scope of this thesis.

The front page picture is taken from [Autoloans.ca, 2018], but couldn't get the source to look proper on the front page.

I wanted to work with my own model, and spent many hours trying to create it, during which I realized that I did not actually know that much about Excel as I thought, or how to use it properly. So after figuring this out, making the model did not take as long as I thought it would, but it serves its purpose very well. The choice of this modelling technique did prove fruitful in the end, as it ended up being very easy to work with, and provided information and customization that I would otherwise not have had access to.

The theory I am using, Choice Awareness, was originally chosen on the assumption that the distribution grid would not work for the future, and therefore I wanted to explore other options for providing the energy demand these vehicles would generate. It also turns out that - at least with the method I used - the distribution network has a long time left before it starts experiencing issues, although this depends entirely on concentration in a given area, not so much on the total demand itself. Some neighbourhoods will experience issues before others, if the residents adopted EVs at higher-than-average speeds.

The problem of this report could perhaps be approached differently, instead of Choice Awareness, look at it from other theoretical perspectives, like Transition Management, as in enabling the transition from fossils to EVs, and enhancing adoption rates through a variety of measures, such as economic or political. Furthermore, the choices could be strengthened or weakened by the inclusion of economics, is it more or less expensive to expand the distribution grid, or to have centralized charge stations? There is definitely the possibility that the results of each scenario might significantly change when looking outside the technological perspectives.

Perhaps another problem that might be expanded on, using the same model, is to try and predict how many charging stations should be available for a given EV amount, and therefore used for planning network expansions and placement of new stations. This model might also be more useful in the context of other countries, that might have weaker grids in comparison to the population of that country.

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Appendices A

A.1 Figure Tables

Table A.2: Figure 4.1

	Workdays	**Holidays**
00:00:00	32000	28000
01:00:00	24000	19000
02:00:00	22000	18000
03:00:00	22000	22000
04:00:00	24000	24000
05:00:00	42000	40000
06:00:00	48000	48000
07:00:00	50000	52000
08:00:00	48000	54000
09:00:00	54000	48000
10:00:00	44000	52000
11:00:00	44000	50000
12:00:00	44000	40000
13:00:00	42000	36000
14:00:00	40000	40000
15:00:00	44000	40000
16:00:00	48000	44000
17:00:00	52000	52000
18:00:00	58000	56000
19:00:00	50000	44000
20:00:00	48000	50000
21:00:00	32000	32000
22:00:00	34000	36000
23:00:00	28000	30000