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# A study of electric vehicle charging patterns and range anxiety

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# Abstract

## A study of electric vehicle charging patterns and range anxiety

*Daniel Knutsen, Oscar Willén*

Range anxiety is a relatively new concept which is defined as the fear of running out of power when driving an electric vehicle. To decrease range anxiety you can increase the battery size or decrease the minimum state of charge, the least amount of power that can be left in the battery, or to expand the available fast charging infrastructure. But is that economical feasible or even technically possible in today's society? In this project we have used a theoretical model for estimating range anxiety and have simulated the average electricity consumption using two different kinds of electric vehicles, to see how often they reach range anxiety according to a specific definition of range anxiety implemented in this model. The simulations were performed for different scenarios in order to evaluate the effect of different parameters on range anxiety. The result that we got were that range anxiety can be decreased with bigger batteries but to get range anxiety just a few times a year you have to use battery sizes which aren't economical feasible today. Despite the shortcomings of todays electric vehicles there are promising new and future technologies such as better batteries which might help alleviate range anxiety for electric vehicle owner. The conclusion from this study is that in the present fleet of electric vehicles is in need of more charging stations and faster charging to get by the problem with range anxiety and having a chance to compete with gasoline and diesel vehicles.

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# 1. Introduction

The electric vehicle isn't a new invention, however the interest for it has increased remarkably during the last couple of years. The EU Commission has proposed that the number of electric vehicles shall be 3.6 % of the total number at 2020, which in Sweden shall means 160 000 when there only exist approximately 2000 in first of April 2013. The Swedish Government has also set a goal to reach a fossil independent vehicle fleet by 2030. [1] Electric vehicles aren't the only eco-friendly option expected to be on the market. Cars driven on hydrogen and biofuel are two options that will be or already are on the market. One big difference is that electric vehicles are more energy efficient than a car with an internal combustion engine, for example biofuel and hydrogen, and will therfore last approximately 3-times as long when you put the same amount of energy in them. [2] Another aspect is that especially hydrogen is very expensive to produce and unstable which has led to some major car producers, for example BMW and Volkswagen, have stopped their research. [3]

One big problem with electric vehicles is that there is not much knowledge about them at car manufacturers and users. [4] One way to increase this knowledge and highlighting the development of electric vehicles is with the new expression range anxiety, the fear of running out of power. When there is no power left in a vehicle the anxiety will be critical and continued progress will be impossible with that vehicle. [5] It is the same type of scenario as gasoline running out in a regular car but a battery electric vehicle can store much less power than a gasoline or diesel vehicle. Range anxiety is a new concept of thinking where there isn't much research however information is needed for both manufacturers and users for understanding the use of electric vehicles better. [4] For the investigations in this report a theoretical model for simulating electric vehicle charging patterns and range anxiety was used. Our report aims to examine how electric vehicles range anxiety is affected by battery size and minimum state of charge, minimum state of charge is the least amount of energy that can be left in a battery without letting it take any damage.

## 1.1 Thesis Questions

- Is there an optimal solution for battery size where the range anxiety never occurs?
- How much is range anxiety affected by decreasing the battery's minimum state of charge by ten percentages points?
- Are the optimal solutions economical feasible?
- Are the optimal solutions technically possible in the near future? If not, are there any other solutions that may solve this problem?

## 1.2 Limitations

Due to time constrains, we will only be looking at one car in each of the different types of electric vehicles, plug in electric vehicles (PHEV) and battery electric vehicles (BEV). This will limit the study to these two types of electric vehicles. For example the simulation results could be different for PHEVs and BEVs. The report is limited because it’s a theoretical analysis where a model has been used to calculate electric load and range anxiety; Range anxiety is defined as how often electric vehicles deplete their battery and not the fear of running out of power. Also the model that is used is stochastic which means that the results will differ, with small variation, for each time running the simulation. The simulation is made for a household of two persons that both work at home and where it is assumed that they only charge the vehicle at home. The simulation is made over a year and for ten households where the mean is then accounted for. We have also made assumptions that some parameters, as energy consumption, stay the same with different values of battery size. In real life this would not be the case, but the difference is negligible. We have also calculated for a charging power of 2.3 kW and not for a faster charging. With which power the charging is made have an impact on the times range anxiety occurs.

## 1.3 Disposition

This report will begin with a background where different important concepts will be explained and information important to the project will be presented. This will be followed by methodology where information about how the simulation, in MATLAB, were made and how the parameters were determined to be as realistic as possible. After that the result will be presented followed by the discussion and conclusion.

# 2. Background

The background aims to provide important information about the model that was used in this project. It also explains the different sorts of electric vehicles that are used in this study.

## 2.1 Electric Vehicles

Electric vehicles are all kinds of vehicles that can be driven on electricity which means that the only environmental pollution is when the electricity is produced and the vehicle itself is produced. Electric vehicles have been around since the early 19$^{th}$ century but the interest for electric vehicles has increased rapidly starting in the early 2000s when the oil prices increased. The attention for electric vehicles increased even more during the late 2000s when the discovery of lithium/ion batteries were made which made the cars lighter, with the same capacity, and also less expensive. [6] The number of battery electric vehicles, BEV, and plug in hybrid electric vehicles, PHEV, two subgroup to electric vehicles, in Sweden has increased by 39 % from the first of January 2013 to the first of April 2013. [5] However according to Rogers Innovation Adoption Diffusion electric vehicles are still in an innovators state which means that they only attract 2.5 % of total market time mode. [4]  For example in Sweden only 0.05 % of all cars in Sweden were BEV or PHEV on first of April 2013.[7] This means that electric vehicles still isn't a very big competitor on the global market and not ready to be promoted yet, however it is a process that just has started. [6]

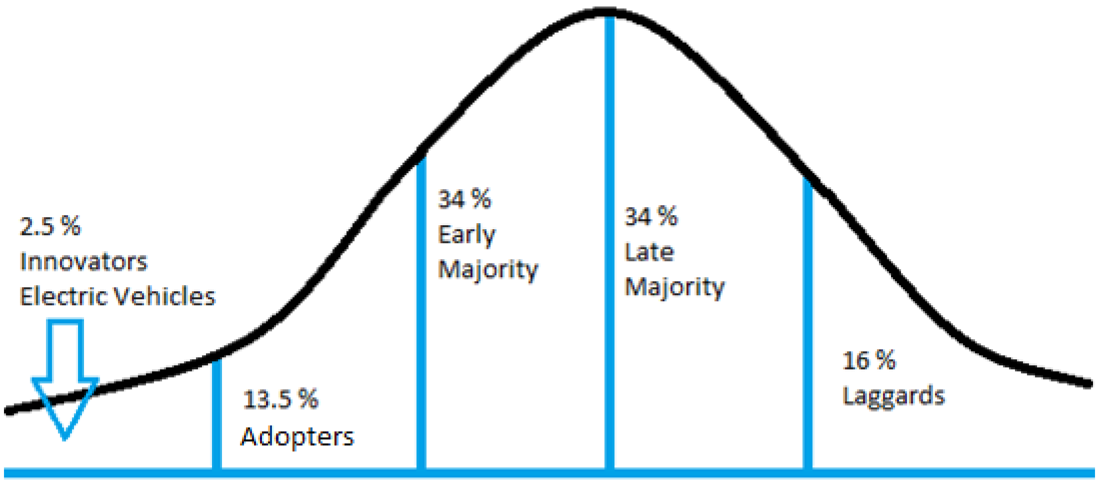


*FIGURE 1. Electric Vehicles is in an innovators state which means that only 2.5 % of the total market is interested in buying them [4]*

### 2.1.1 Battery Electric Vehicle, BEV

A battery electric vehicle only uses an electric engine and a battery that can be charged by plugging it to the power grid. [8] The charging is done simply by connecting the vehicle and the power source with a cable. There's different kind of charging types but the most common is type 1 and type 2, see section Different Types of Charging. [9] The big difference between BEV and PHEV is that the BEV hasn't got any other alternative power source, as a combustion engine, which means that when the battery is empty the vehicle can't be driven. [8-9]

### 2.1.2 Plug in Hybrid Electric Vehicle, PHEV

Plug in hybrid electric vehicles get power using a combination of an electric engine and a combustion engine that kicks in when the battery runs out of charge. The difference between PHEV devices is the potential to recharge the battery by plugging it into the power grid, were hybrids electric vehicles, HEV, instead charge the electric engine with the combustion engine. PHEV also have a bigger battery than a HEV usually have. To reduce the emissions HEV only uses the combustion engine, if possible, when driving over approximately 50 km/h. PHEV is therefore a more energy and resource efficient choice than a conventional hybrid vehicle. [8]

## 2.2 Battery material

The batteries most used in electric vehicles are Lithium-ion batteries. However, as seen in the figure 2 research are made on other alloys which will increase the capacity of the battery, which means less weight to the vehicle and therefore lowering the energy consumption. For example a lithium ion battery has usually the density 150-300 Wh/kg. However, if succeeded to produce Lithium/Air battery the density is expected to increase at least to 600 Wh/kg. lithium/air batteries are likely to be used in Toyota cars by 2020. [10]

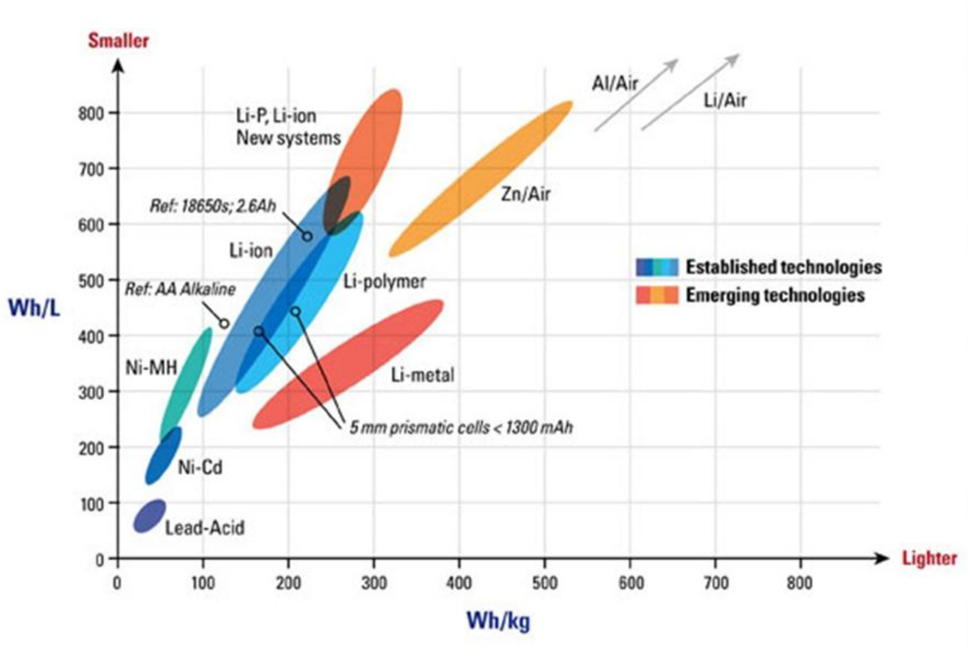


*FIGURE 2. Different types of battery density used in electric vehicles. (image reference: http://homework.uoregon.edu/pub/class/hc441/bstorage.html)*

## 2.3 Minimum State of Charge

Minimum state of charge is the least amount of power that should be left on the battery. This limit exists because the battery should not be charged down to zero and therefore have battery manufacturer chosen to add a minimum state of charge. Without the minimum state of charge the battery's lifespan would decrease remarkably which means this feature is important both for economics and the battery's quality. [11]

## 2.4 Economy

Economy is an important factor when choosing a car. In a study made by Vattenfall 37 % of the Swedish population could consider buying an electric car the next time they purchase a new car if the price could be compared to a regular car. [12] The current price for one kWh in a battery is 700 US$. This number is expected to decrease, provided that no technological breakthrough occurs, to 400-450 US$ in the year 2020 [9] which will lead to doubled capacity to almost the same price.

Another important factor in the price for a vehicle customer is the fuel price. With the oil prices rising we will see prices for gasoline and diesel increasing. This will make electric vehicles more attractive, with the price of electricity being somewhat more stable than oil prices. The annual fuel cost of electric and gasoline cars can be estimated to show how the yearly cost differ for the different types of cars. [13] Note that the gasoline prices in USA are lower than it is in Europe which means that the difference is even more in Europe.

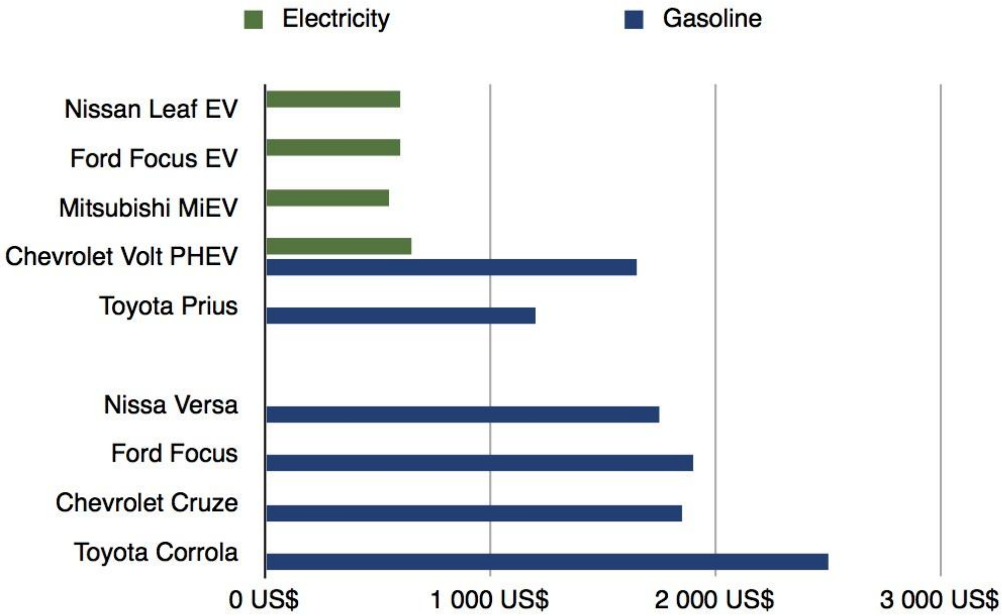


*FIGURE 3. Estimated fuel cost over a year for different cars based on American gasoline and electricity prices, Chevrolet Volt is counted as only driving on electricity or gasoline [13]*

## 2.5 Range Anxiety

Range anxiety is according to the Oxford Dictionary defined as "*worry on the part of a person driving an electric car that the battery will run out of power before the destination or a suitable charging point is reached*". [5] Range anxiety is a relatively new phenomenon in car development and tries to point on the problem that electric vehicles manufactures has to overcome to compete with gasoline and diesel vehicles. Range anxiety is hard to measure because it is a definition of the drivers feeling, but in this report it is assumed that range anxiety can be counted as when the car actually runs out of power.

## 2.6 Different types of charging

There are a number of different types of charging stations being used for electric vehicles. They vary in for example different sockets, different currents and different power. The sockets on the charging station side most commonly used are the so called shucko connector and type 2 for AC charging. On the car side the sockets for AC charging is called type 1 and type 2 and CHAdeMO for fast DC charging. A type 1 connector can charge between 1,3 kW up to 7,4 kW, and a type 2 connector could charge between 1,3-43.5 kW depending upon the car and the cable used. CHAdeMO is a fast DC charging which means it can charge up to 50 kW DC if the car is compatible. The EU Commission has proposed that the type 2 socket shall be the standard for normal charging on charging station from 2017, this is also the connector used by the Swedish charging infrastructure suppliers. Tesla Motors have a fast DC charging which can reach up to 120 kW which would charge a battery of 85 kWh in approximately half an hour which would take between 12-24 hours for type 1 charging. The EU Commission together with the ACEA has also proposed a new fast DC charging standard called CCS or Combo T2, that could charge up to 170 kW. This is also supposed to be implemented fully by 2017. [9] [14] There are right now 402 public charging spots with a total of 1252 sockets in Sweden, but the numbers are increasing. [15] For more information about were different charging spots are located see [15].

### 2.6.1 Conductive feeding while driving

An alternative method for charging electric vehicles, which is still under development, uses a well-established technique of feeding the vehicles directly with electricity when the vehicle is moving, this method is called conductive feeding. Conductive feeding works simply by feeding electricity from the road to the car with the use of an extension arm, test have showed that extensions arms under the car is superior to a solution with an extension arm over the car. This extension arm can then be lower when the vehicle need to recharge its battery, the electricity then goes either directly to the motor or being stored in the battery. A problem with conductive feeding is the risk of obstacles on the road. This may be solved by using sensors to indicate when there are obstacles, like small stones or gravel, on the rail but this would increase the total cost. For the moment the developers are testing the method on a test track outside of Arlanda but the solution of conductive feeding is still in an early stage of development and has a long way to go before it will even be a feasible solution. [16]

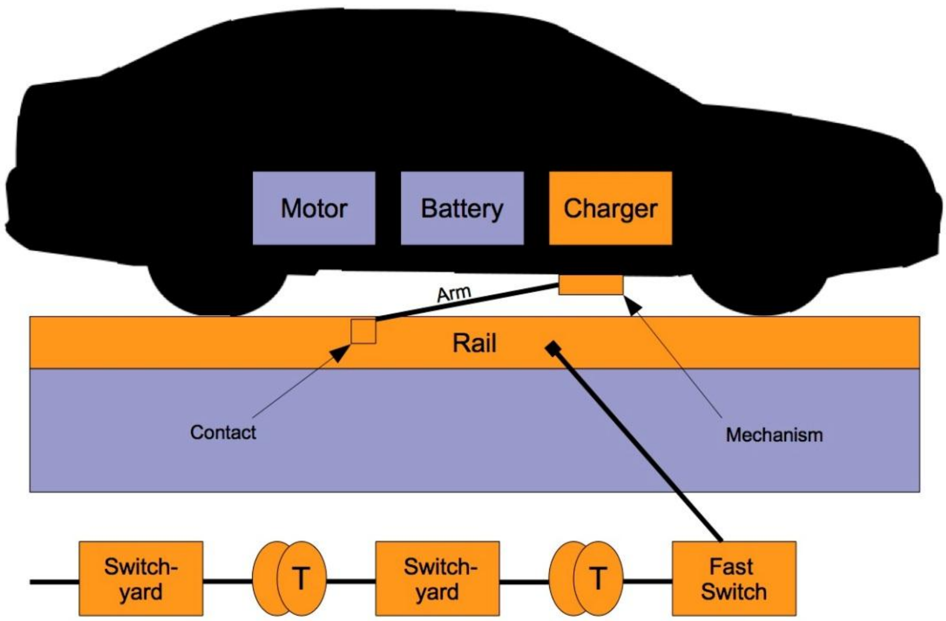


*FIGURE 4. An illustration of a conductive feeding. High voltage cables are transformed to lower voltage cables that then electrify the rail. A contact mounted on the end of the arm delivers electricity to the charger, that then either store electricity in*

*the battery or powers the motor. A mechanism controls the arm so it can be extended when there's need of power or retract it if there's obstacles in the rail. [16]*

### 2.6.2 Inductive charging

Inductive charging is an upcoming technology which is a wireless choice for charging. It is basically installing a plate in the ground where you commonly park the car. When the car is parked, electricity will be transferred to the cars battery automatically and entirely wireless instead of connecting cables to the vehicle every time charging is needed. Inductive charging is expected to be on the market in a couple of years. [17]

*FIGURE 5. Showing how a car is charged with inductors. (Image reference: Vattenfall, http://newsroom.vattenfall.se/2011/02/02/vattenfall-skapar-framtidens-laddningslosningar-for-elbilar/)*

# 3. Methodology

In this methodology chapter the model used to simulate the different events will be explained. Methodology will also present the different parameters that were assumed to get realistic simulations.

## 3.1 PHEV Home Charging Model

The model used in this paper was developed in [11]. The home charging model for electric vehicle load is a Markov-chain model for generating synthetic household activity patterns and electricity use developed by J. Widén. [18-19] A Markov-chain model is a stochastic model based on a number of states. For each time-step the model is in one of the states and there is a probability associated with the transition from one state to another in the next time step. The Markov-chain model developed for household electricity use [18-19] had states such as cooking and dishwashing but also a state of "away" from the house. The plug in electric vehicle model assumed that an electric vehicle was used during a certain percentage of the states 'away', and plugged in for charging when arriving at home. For more information on the Markov-chain model see [18-19]. With some assumption from Joakim Munkhammar [20] this model could also be used to calculate how often range anxiety happened to the PHEV which in this case meant when the cars electric battery runs empty and started to run on its hybrid engine instead. [11] A mathematical description of the electric vehicle part is provided below.

If the car is not 'away' it will be assumed to be connected to the grid and will consume electricity until it is fully charged, if not connected the electricity consumption would be zero. [11] This creates a load, generated by the vehicles charging, on the household load $P_{PEV}(t)$ at time t which can be expressed according to the equation [21]:

$$P_{PEV}(t) = \begin{Bmatrix} C_p & \textit{if charging}, \\ & 0 \quad \textit{else.} \end{Bmatrix} \tag{1}$$

When the program calculates range anxiety it uses the same model as described above. Range anxiety in this case is defined as when the vehicle doesn't have power left and can't be driven. This is of course a simplified assumption regarding the human feeling of range anxiety, but in order to make a relatively simple yet feasible model this assumption had to be made. In the model the electric vehicle was assumed to be plugged in and charged –until fully charged - when returned home. This model does this in an easy way by checking whether the car is 'away' or not, and if 'away' withdrawing electricity from the car battery by using the earlier state of charge and subtracting it with the average velocity multiplied with the average consumption, see equation 2. The new state of charge will be defined using the following equation [22] :

$$SOC_{i+1} = \begin{Bmatrix} SOC_i - \dfrac{v \cdot \zeta}{60} \;\; \textit{if } A_{1i} = 1,\, k < p_{car},\, DOD < SOC_i \\ SOC_i + \dfrac{C_p}{60} \;\; \textit{if } A_{1i} \neq 1,\, SOC_i \leq SOC_{max} \end{Bmatrix} \tag{2}$$

*TABLE 1. Parameters used in equation (1) and (2)*

| Parameter | Symbol |
|---|---|
| Initial state of charge [kWh] | $SOC_{max}$ |
| State of charge at time *i* [kWh] | $SOC_i$ |
| Depth of distance, minimum state if charge [kWh] | $DOD$ |
| Charging power [kW] | $C_p$ |
| Probability of take car [%/100] | $p_{car}$ |
| Average engine consumption [kWh/km] | $\zeta$ |
| Velocity [km/h] | $v$ |
| If driving 1, else 0 | $A_{1i}$ |

Aspects such as car weight are not explicitly included in the parameters, but can be implicitly included in for example average energy consumption. The first value of the batteries' state of charge depends on the starting value of the battery size, because the program assumes that the battery is fully charged by the start of the simulation. It is not only the battery size that has a big effect on the batteries' maximum effect; The minimum state of charge is also a very important constant. This value exists because the battery should not be charged down to zero because it reduces battery life time.. If the state of charge reaches the minimum state of charge it is assumed that it cannot deliver more power, and the EV has to be charged to be operational again. The model counts the number of times the state of charge hits the minimum state of charge and display how many times the minimum state of charge is reached, and this is assumed to be a measure of the human feeling of range anxiety. It should be noted that this measure of range anxiety is perhaps best seen as a relative measure, that one configuration has more or less range anxiety than another configuration. To get a mean value of the range anxiety the model runs a separate simulation for different households, the standard value of the model is five apartments where each is occupied by two persons. In this case, MATLAB was used to implement the model and to run simulations. [11]

## 3.2 Simulation

To get realistic data for the electric vehicle in the simulation we chose to look at two electric vehicles on the market, with easy accessible data. These two cars were Nissan Leaf (BEV) and Chevrolet Volt (PHEV). The model is made for usage of a PHEV, but we used it on BEV as well which means that if range anxiety is reached we simply assume that the BEV is transported home in some way. After the simulations were done we compared the results and for the different cars we tried to find an optimal solution on their battery size where range anxiety never occurred. We also checked how much their range anxiety would differ if we decreased their respective minimum state of charge with ten percentage points.

## 3.3 Data

The different important parameters that will make a difference in the simulation of range anxiety are as follows:

- **Battery Size:** The size of the battery in the simulated BEV and PHEV. (measured in kWh)
- **Energy Consumption:** How much power the car drains per kilometre. This parameter is mostly affected by the weight of the car. (measured in kWh/km)
- **Charging:** With which power the battery is charged determining how fast the battery is charged. (measured in kW)
- **Minimum State of Charge:** What percentage of the total battery that can be used without letting the battery take any damage when charging. In this report minimum state of charge means that there is no power left for driving. (measured in percentage)

### 3.3.1 Battery size

The battery sizes for the different cars are 16 kWh for Chevrolet Volt [23] and 24 kWh for Nissan Leaf. [24] In the simulation we added 10, 50 and 100 kWh to the existing value for the different car's to see how much the range anxiety was affected by size.

### 3.3.2 Energy Consumption

The model for electric vehicle charging was equipped with a seasonal parameter so that the energy consumption was varied over seasons in order to reflect the different need for example internal heating and battery efficiency [11]. The parameter values were: 0.8 for summer, 1.2 for winter and 1 for spring/fall, making the average energy consumption the same over a year which were 0.135 kWh/km for Chevrolet Volt [23] and 0.1734 kWh/km for Nissan Leaf. [24]

### 3.3.3 Charging

Both cars get charged with the power 2.3 kW. [11]

### 3.3.4 Minimum state of charge

To get information for the minimum state of charge we had to use values for estimated range, which were approximately 120 kilometres for Nissan Leaf [25] and 80 kilometres for Chevrolet Volt [23]. Together with the values for estimated range, battery size and energy consumption we could easily calculate the minimum state of charge with equation (3).

$$Minimum\ State\ of\ Charge = 1 - \frac{Energy\ Consumation \cdot Estimated\ Range}{Battery\ Size} \quad (3)$$

That led to the minimum state being 32.5 % for Chevrolet Volt and 13.4 % for Nissan Leaf. All the values can be seen in table 2 below.

*TABLE 2. The different data for the two cars.*

| Parameter\Car | Chevrolet Volt (PHEV) | Nissan Leaf (BEV) |
|---|---|---|
| Battery Size | 16 kWh | 24kWh |
| Minimum State Of Charge | 32.5 % | 13.4% |
| Charging | 2.3 kW | 2.3 kW |
| Energy Consumption | 0.135 kWh/km | 0.1734 kWh/km |

# 4. Results

Here follows the results from our simulations. First we will show the battery state of charge change over a year for the different value of battery size, to give a better picture we will also show the results for a week for one of the simulations. Second we show how the state of charge depends on the minimum state of charge, this will only be done for one reduction of the minimum state of charge by ten percentage points. Then follows a graph that shows how the range anxiety changes with different battery sizes. In the end the economics associated with charging and battery will be presented.

## 4.1 Battery Size and Minimum State of Charge

### 4.1.1 Chevrolet Volt

The standard value for Chevrolet Volt gave range anxiety 0.2838 times per day which over a year resulted in circa 104 times. Figure 6 show how the battery's state of charge differ over a year. Figure 7 shows the same thing as in figure 6 except it is only showing 5 days in June. Range anxiety occurs when the state of charge reach the minimum state of charge, this can easily be seen by looking at the density of lines near the minimum state of charge.

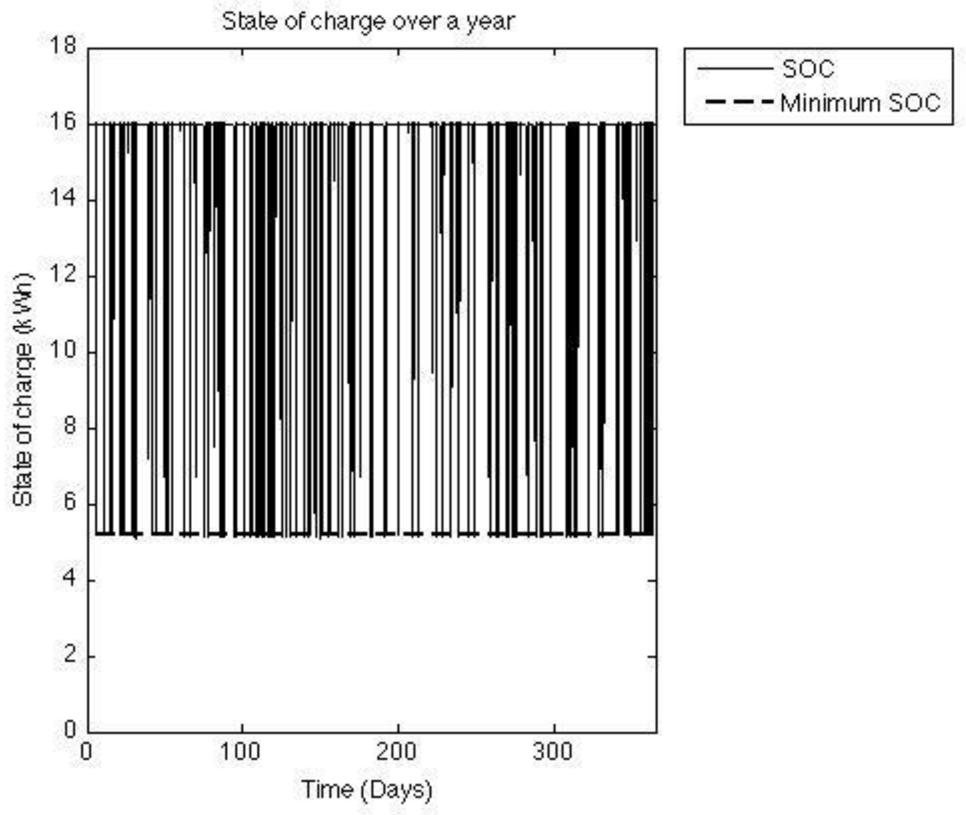


*FIGURE 6. The battery's state of charge simulated over a year for a 16 kWh battery and 32.5 % minimum state of charge*

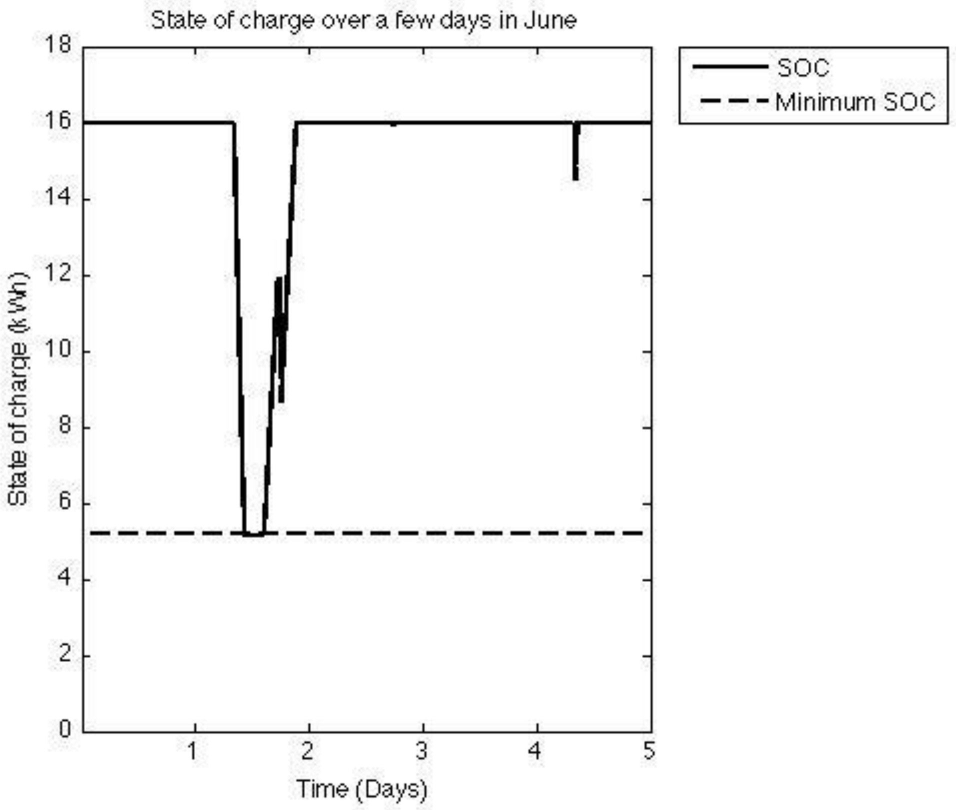


*FIGURE 7. An example of the state of charge for five days in June*

When increasing the battery size to 26 kWh the range anxiety occurred 0.2245 times per day which over a year resulted in circa 82 times which can be seen in figure 8.

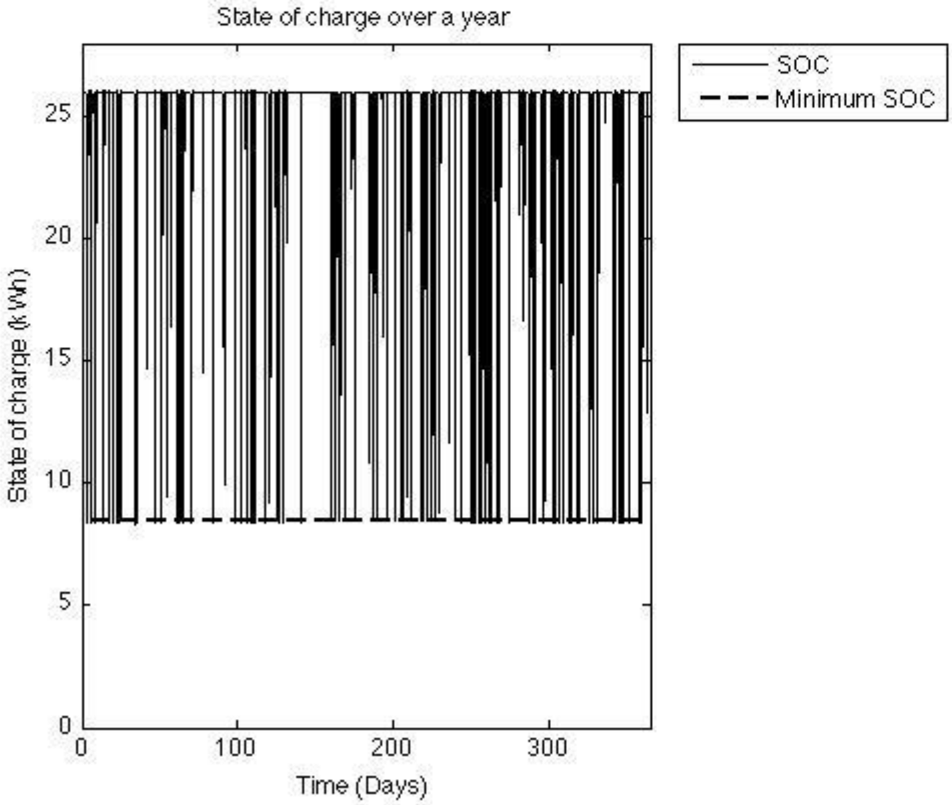


*FIGURE 8. The battery's state of charge simulated over a year for a 26 kWh battery and 32.5 % minimum state of charge*

When increasing the battery size to 66 kWh range anxiety occurred 0.1049 times per day which over a year resulted in circa 38 times which can be seen in figure 9.

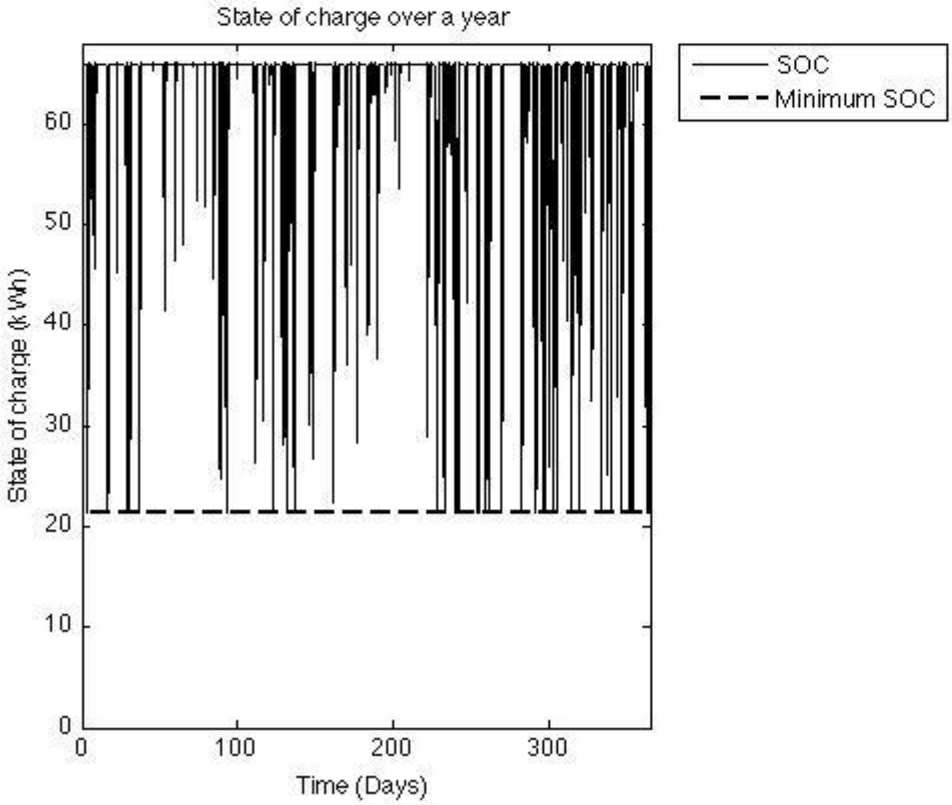


*FIGURE 9. The battery's state of charge simulated over a year for a 66 kWh battery and 32.5 % minimum state of charge*

When increasing the battery size to 116 kWh the range anxiety occurred 0.0263 times per day which over a year resulted in circa 10 times which can be seen in figure 10.

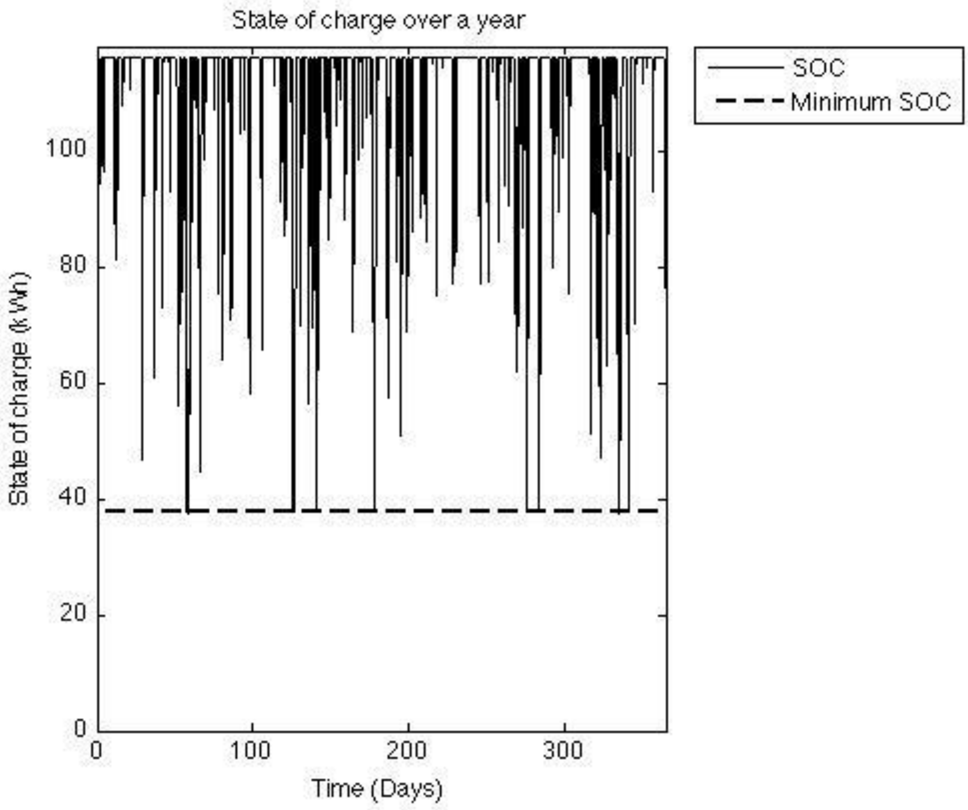


*FIGURE 10. The battery's state of charge simulated over a year for a 116 kWh battery and 32.5 % minimum state of charge*

When instead only decreasing the minimum state of charge from 32.5 % to 22.5 % range anxiety occurred 0.2707 times per day which over a year resulted in circa 99 times which can be seen in figure 11.

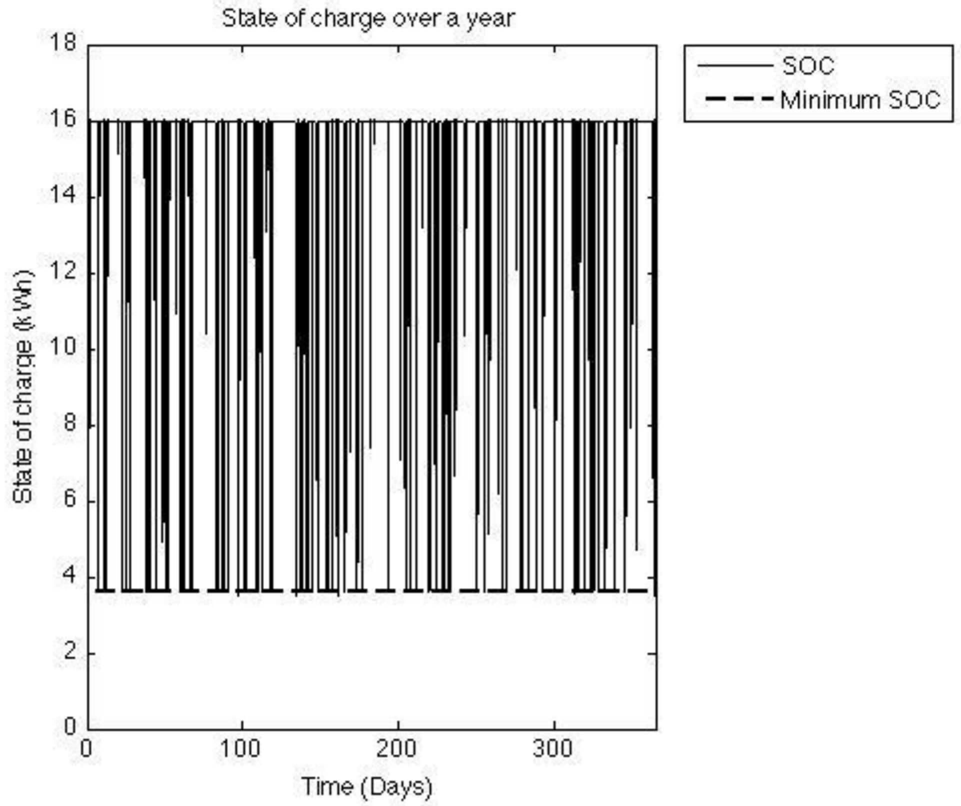


*FIGURE 11. The battery's state of charge simulated over a year for a 16 kWh battery with 22.5 % minimum state of charge*

### 4.1.2 Nissan Leaf

The standard value for Nissan Leaf gave range anxiety 0.2352 times per day which over a year resulted in circa 86 times which can be seen in figure 12..

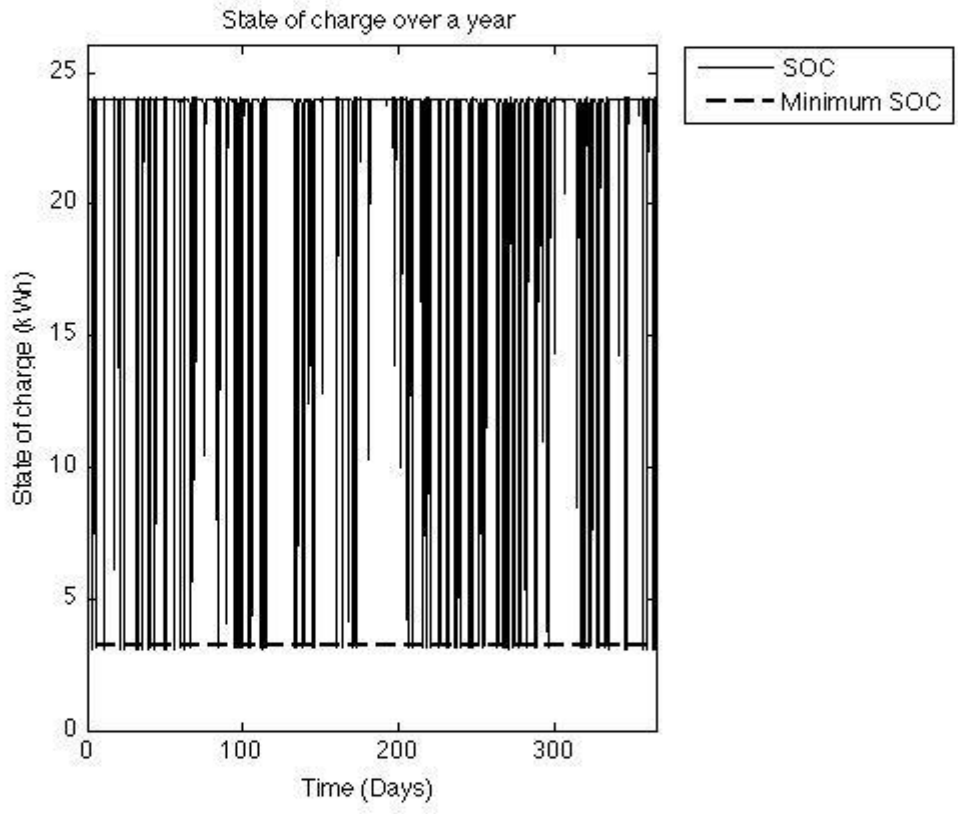


*FIGURE 12. The battery's state of charge simulated over a year for a 24 kWh battery and 13.4 % minimum state of charge*

When increasing the battery size to 34 kWh the range anxiety occurred 0.1945 times per day which over a year resulted in circa 71 times which can be seen in figure 13.

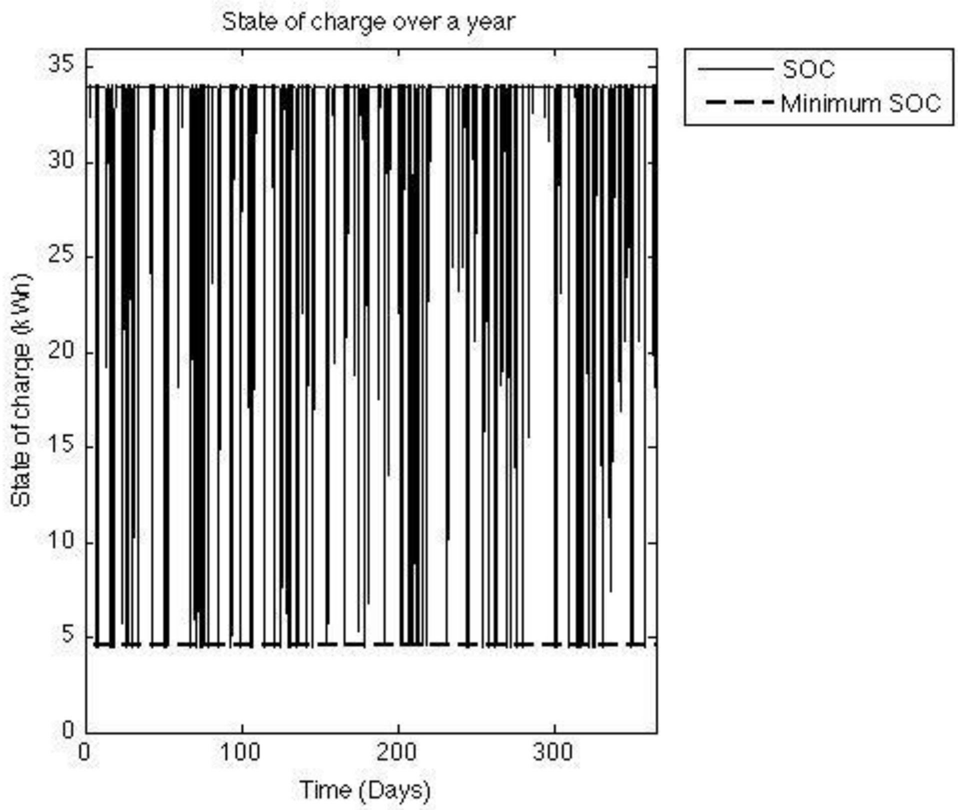


*FIGURE 13. The battery's state of charge simulated over a year for a 34 kWh battery and 13.4 % minimum state of charge*

When increasing the battery size to 74 kWh range anxiety occurred 0.1049 times per day which over a year resulted in circa 38 times which can be seen in figure 14.

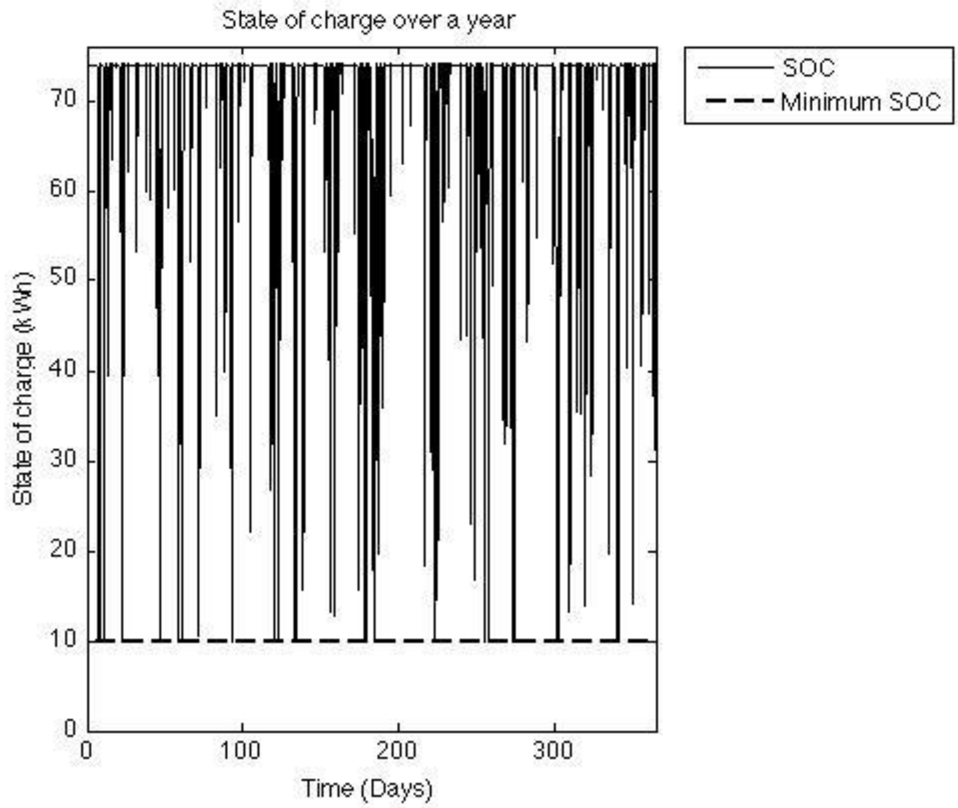


*FIGURE 14. The battery's state of charge simulated over a year for a 74 kWh battery and 13.4 % minimum state of charge*

When the battery size was increased to 124 kWh the range anxiety occurred 0.0263 times per day which over a year resulted in circa 10 times which can be seen in figure 15.

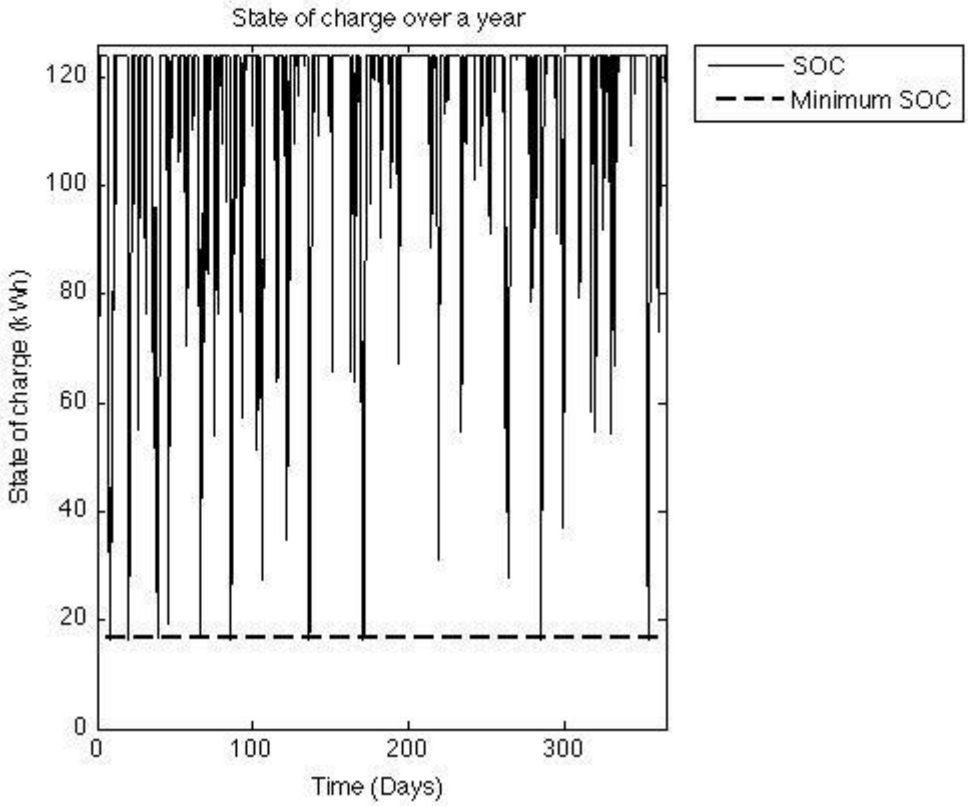


*FIGURE 15. The battery's state of charge simulated over a year for a 124 kWh battery and 13.4 % minimum state of charge*

When instead only decreasing the minimum state of charge from 13.4 % to 3.4 % range anxiety occurred 0.2315 times per day which over a year resulted in circa 85 times which can be seen in figure 16.

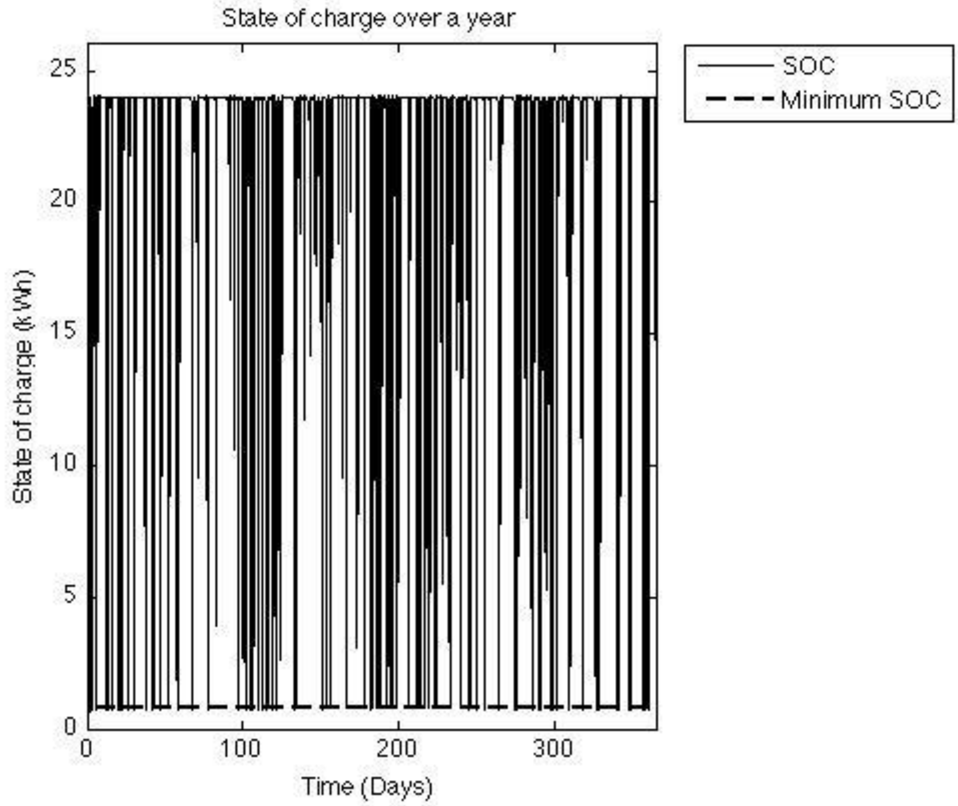


*FIGURE 16. The battery's state of charge simulated over a year for a 24 kWh battery and 3.4 % minimum state of charge*

### 4.1.3 Table of the Results

Here follows two tables with the complete results for different battery sizes and state of charges for Nissan Leaf and Chevrolet Volt.

*TABLE 3. The values used when simulating the Chevrolet Volt*

| Battery Size | 16 kWh | 26 kWh | 66 kWh | 116 kWh | 16 kWh |
|---|---|---|---|---|---|
| Minimum State of Charge | 32.5% | 32.5% | 32.5% | 32.5% | 22.5% |
| Energy Consumption | 0.135 kWh/km | 0.135 kWh/km | 0.135 kWh/km | 0.135 kWh/km | 0.135 kWh/km |
| Range Anxiety, per day | 0.2838 times | 0.2245 times | 0.1049 times | 0.0263 times | 0.2707 times |
| Range Anxiety, per year | 104 times | 82 times | 38 times | 10 times | 99 times |

*TABLE 4. The values used when simulating the Nissan Leaf*

| Battery Size | 24 kWh | 34 kWh | 74 kWh | 124 kWh | 24 kWh |
|---|---|---|---|---|---|
| Minimum State of Charge | 13.4% | 13.4% | 13.4% | 13.4% | 3.4% |
| Energy Consumption | 0.1734 kWh/km | 0.1734 kWh/km | 0.1734 kWh/km | 0.1734 kWh/km | 0.1734 kWh/km |
| Range Anxiety, per day | 0.2352 times | 0.1945 times | 0.0932 times | 0.0279 times | 0.2315 times |
| Range Anxiety, per year | 86 times | 71 times | 34 times | 10 times | 84 times |

## 4.2 Range Anxiety

Here follows a graph to illustrate how range anxiety decreases with increasing battery sizes. The Y-axis is defined as how many times range anxiety is reached per day. The figure shows that range anxiety is decreasing exponentially with increasing battery size.

The reason why Volt and Leaf follow the same pattern, despite different starting values, depends on the ratio of minimum state of charge and energy consumption. The value of range anxiety will move towards zero but will never reach it, the reason why this happens is because increasing battery size comes with charging time being so long that the battery will almost never be fully charged between drives. Measurements are made starting at the standard battery size for Volt (16 kWh) and Leaf (24 kWh) with an interval of 10 kWh to the maximum value, that in this report is set to 116 respectively 124 kWh. Irregular values in the graph depend on the variate in the MATLAB code.

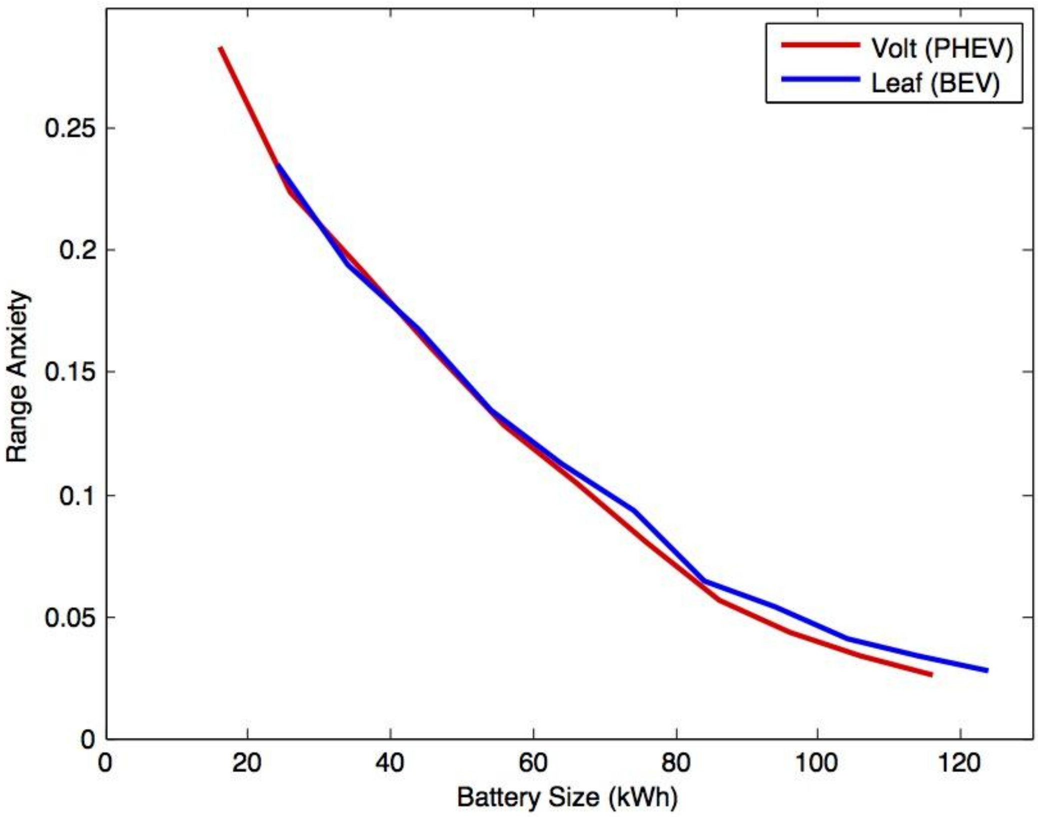


*FIGURE 17. The relation between range anxiety and battery size.*

## 4.3 Economy

### 4.3.1 Charging pattern

With increasing battery sizes comes increasing charging time. This will be, assumed that the charging method isn't revolutionise in the near future, a big problem for electric vehicles. To illustrate this problem the charging pattern for the standard value and the largest value, that's used in this report, for the battery sizes are tested for 20 household in one year. Also electricity consumption for other appliances in the household is shown for comparison to the electric vehicle charging consumption.

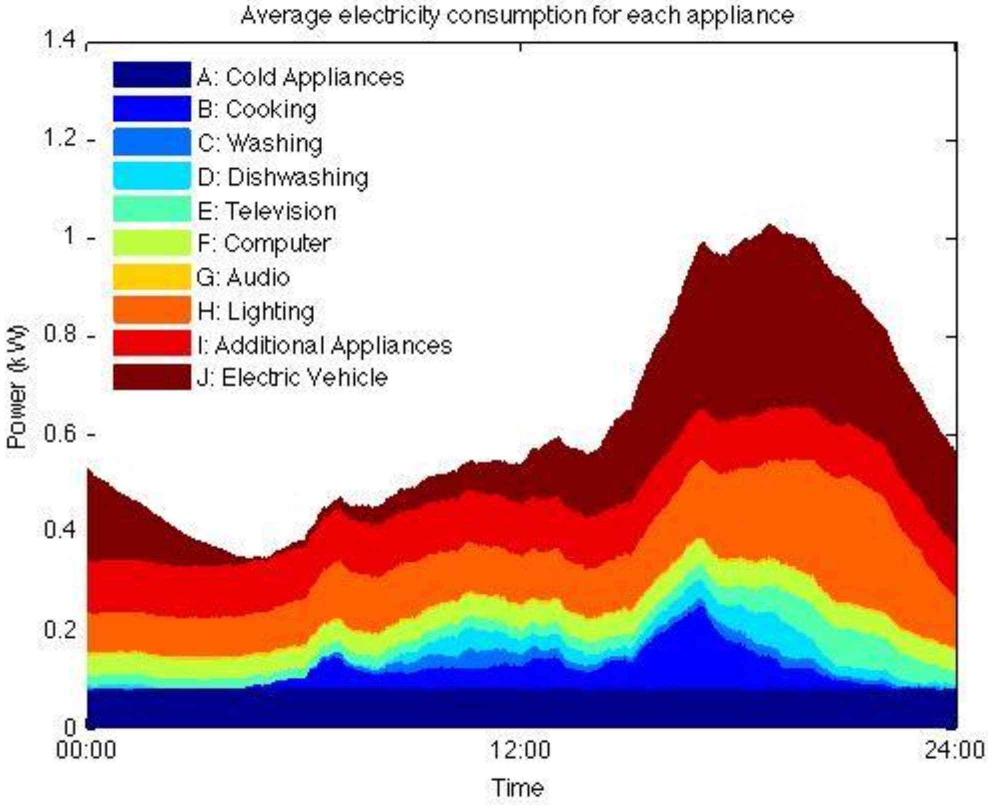


*FIGURE 18. The mean charging pattern for a Chevrolet Volt, with battery size 16 kWh. The household electricity use from the Markov-chain model is also included in this figure*

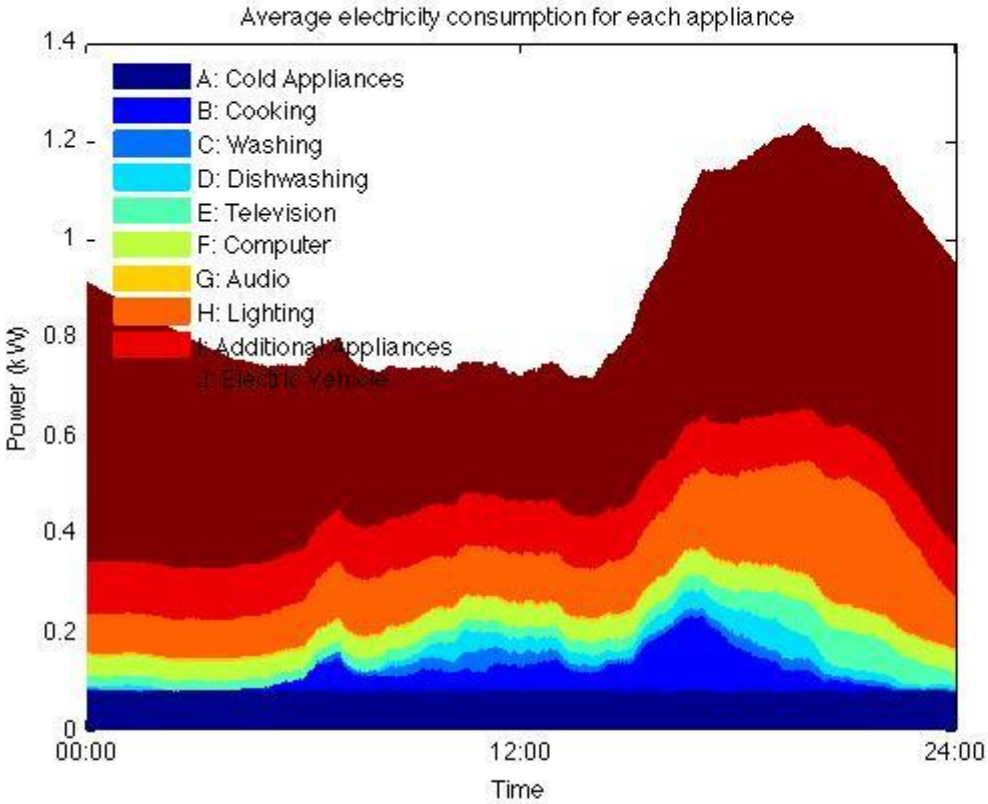


*FIGURE 19. The mean charging pattern for a Chevrolet Volt, with battery size 116 kWh. The household electricity use from the Markov-chain model is also included in this figure*

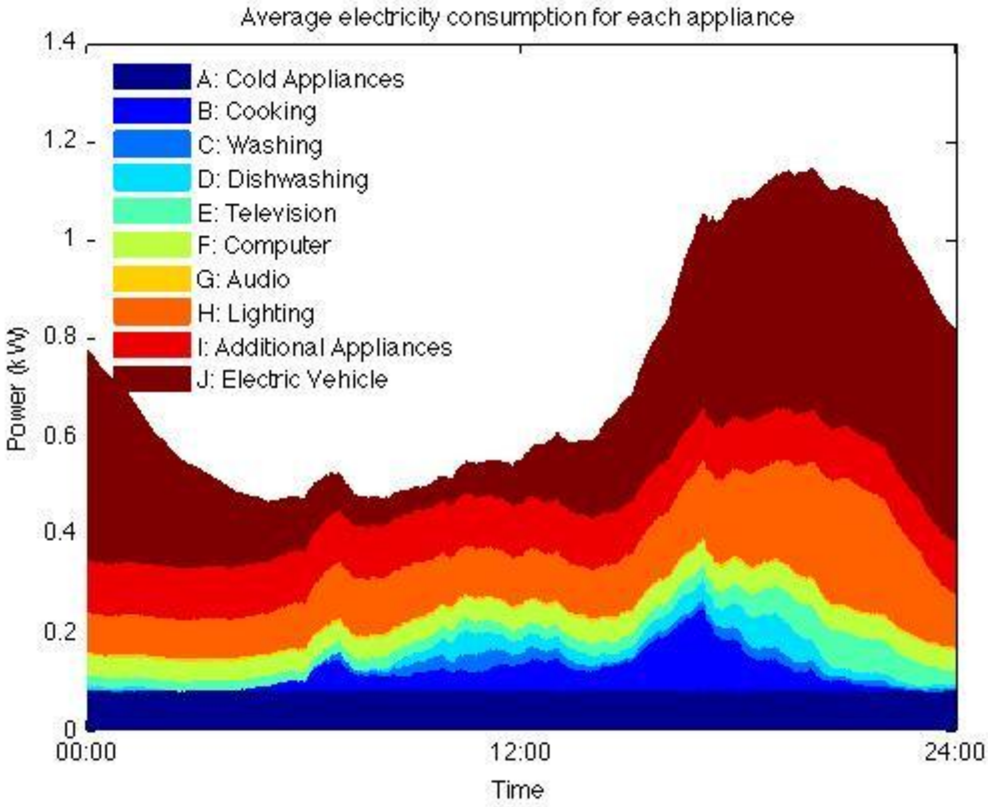


*FIGURE 20. The mean charging pattern for a Nissan Leaf, with battery size 24 kWh. The household electricity use from the Markov-chain model is also included in this figure*

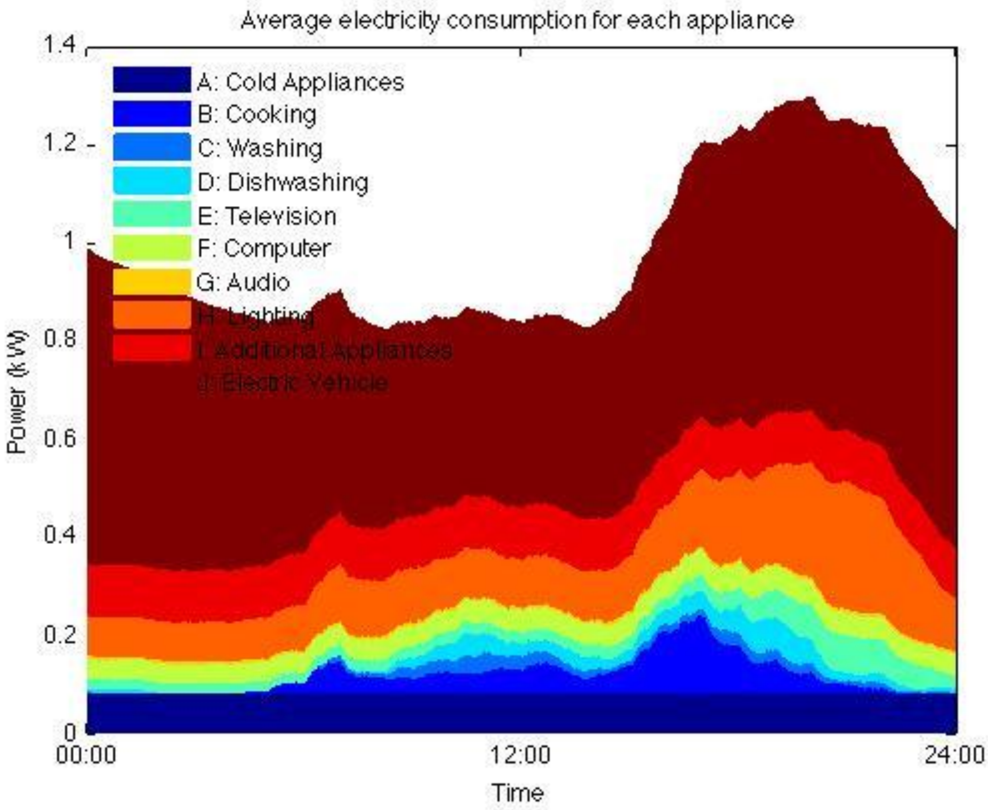


*FIGURE 21. The mean charging pattern for a Nissan Leaf, with battery size 124 kWh. The household electricity use from the Markov-chain model is also included in this figure*

### 4.3.2 The cost of the battery

There are different costs associated with different sizes of battery. Down below are tables over how much the different batteries costs today and how much they are expected to cost in 2020, one best scenario and one worst scenario. The numbers are calculated by taking the values of the battery size times the value of how much 1 kWh costs today and will do in 2020.

*TABLE 5. The cost for Chevrolet Volt battery (US$)*

| Battery size\Year | 2013 | 2020 |
|---|---|---|
| 16 kWh | 11200 | 6400-7200 |
| 26 kWh | 18200 | 10400-11700 |
| 66 kWh | 46200 | 26400-29700 |
| 116 kWh | 81200 | 46400-52200 |

*TABLE 6. The cost for Nissan Leaf batteries (US$)*

| Battery size\Year | 2013 | 2020 |
|---|---|---|
| 24 kWh | 16800 | 9600-10800 |
| 34 kWh | 23800 | 13600-15300 |
| 74 kWh | 51800 | 29600-33300 |
| 124 kWh | 86800 | 49600-55800 |

# 5. Discussion

In discussion our own thoughts will be explained.

## 5.1 Optimal Solution for Battery Size

One conclusion from the simulations is that there is no optimal solution for which range anxiety is zero. If you increase the battery size even further the range anxiety would most likely disappear. However, in Figure 17we can see that the range anxiety is decreasing exponentially, as explained earlier the reason depends on the relation between bigger battery size and charging time.

Another important factor with increasing battery size is that the weight of the vehicle will increase and so would the energy consumption. This factor isn't being analyzed in this report due to limitations and difficulty with implementing this in the MATLAB code but it has to be highlighted. One solution to the problem is batteries with higher energy density. These would decrease the total weight hence reduce the energy consumption. However as we mentioned earlier these batteries only double the capacity against those that already exists which means the vehicles is going to get heavier anyway if we want batteries that are as big as 100 kWh. So further studies analyzing the energy consumption could be interesting.

Quicker charging is also an interesting factor that can be analyzed. Sometimes when charging with 2.3 kW the battery doesn't get fully charged which means that maybe half of the battery is being used, which can be seen in figure 8. With quicker charging this problem wouldn't occur as often which should lead to range anxiety occurring less often. Quicker charging also gives the advantage of being able to use your car more often. For example if your cars battery is near minimum state of charge and you have an important meeting in 2 hours, it would perhaps be nicer to know that your car is fully charged because of the quicker charging than driving with only half battery capacity with constant anxiety. To conclude, quicker charging both decrease range anxiety and increase user benefits.

## 5.2 Decreasing the Minimum State of Charge

From our simulations we couldn't observe that decreasing the minimum state of charge made very much difference for the result, not at least for small battery sizes. When decreasing Chevrolet Volt minimum state of charge with ten percentage points the only difference was that the car could drive on 1.6 kWh more which is approximately 13 kilometers more. When decreasing the minimum state of charge on a big battery the number of kilometers the car can be driven will be more than for a small battery which maybe could be interesting in the future. However from our simulations it seems more appropriate to research for increasing the battery capacity and in this way decrease range anxiety. Also minimum state of charge exists for letting the car's battery last longer and is therefore good to keep intact.

## 5.3 Economical Feasibility

The problem with range anxiety is that if you decrease the numbers of time range anxiety occurs you also increase the cost of the electric vehicles. One particular conclusion of this project is that less range anxiety means more expensive batteries and more expensive charging. If we start with more expensive batteries then it's easy to see in table 5 and 6 that more kWh means higher cost for the battery. However we also saw that the price for kWh battery capacity will decrease to approximately the half in just 7 years. This means that batteries with the double capacity can be used to the same price. This will not solve the problem, however increase the range the electric vehicles can be driven which makes electric vehicles more attractive. To increase the battery to optimal sizes where range anxiety only occurs less than ten times a year would require very expensive batteries, prices no one today is prepared to pay. Even in 7 years time the price of batteries would be approximately 45 000 US$. This isn't reasonable, however if the prices per kWh is decreasing in the same pace as now it's possible that it would be a solution in the future.

According to our results charging bigger batteries will cost more energy and have longer charging time, which can be seen in figure 18-21, hence the cost would be bigger for the household compared with the costs associated with electric vehicle charging when range anxiety limits the driving range. Even if we start using quicker charging, which we discussed to decrease the range anxiety for bigger batteries, the cost for charging these batteries would be the same and it would generate even higher peaks in the electric grid. These peaks in the electric grid would be problematic, especially when people usually charge their cars in the afternoon when they come home from work and during the night, see figure 18-21, where most energy is already used in the household. This would lead to a demand of high power and in countries with low or even non access to renewable energy this would probably mean that use of fossil fuel would increase.

## 5.4 Technically Possibilities

The results indicate that optimal solutions to problems of range anxiety might are not achieved in the near future. The development of batteries is slow; Looking at figure 17 we see that a lot bigger batteries is needed to even decrease the range anxiety by half the range anxiety and this is a big problem in the future for electric vehicles. If the manufacturers can't lower the range anxiety to near zero, electric vehicles won't be able to compete with gasoline and diesel cars. But range anxiety will never be zero, not in the near future, we need to add other solutions. The simplest one is to increase the coverage of charging stations. Problems with charging stations are the vast number of different types of charging. This may be solved with adapters, but this always comes with power losses. If the numbers of charging stations are going to increase we have to get a standard type for charging if the increases of coverage are going to include all electric vehicles, but with EU Commission standardizing the charging type this may not be a problem in the future. Inductive charging seems like an interesting solution which will make it more comfortable to use electric vehicles. Another solution, conductive feeding, may work but has a long way ahead for it to even is economical considerable or practical, but it is a solution. If the EU Commision are going to reach their goal of 3.6 % electric vehicles at 2020 they have to deal with range anxiety.

It can be noted that range anxiety basically only affects BEV. When plug in hybrids runs out of battery power, they simply use the combustion engine to continue driving and can recharge the battery when there is access. There is however some sort of range anxiety for drivers of hybrid vehicles; Economic and environmental thinking is factors that affect drivers to want to drive as far as possible with electric power. You could call this "luxury anxiety" since it is not really the same as for drivers of pure electric vehicles.

# 6. Conclusion

Range anxiety is a big problem for electric vehicles to overcome and has to be solved if it's going to have a realistic chance to compete with diesel and gasoline vehicles. There's only so much you can do by increasing the battery size and decreasing the minimum state of charge.

What our results shows instead is the importance of a working infrastructure for electric vehicles; like increasing the numbers of charging stations, faster and better charging, conductive charging while driving and so on. However a lot of these solutions aren't economically or technologically possible right now and that makes electric vehicles a project in the innovator's state. This means that sudden changes, like rushing the process of changing to electric vehicles, possible would not affect the market positively because it might not be ready for that kind of changes yet. If the research in the battery area and some of the technical possibilities proceed as planned then electric vehicles will make, what we believe is, an optimal solution in the near future.

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