Individual Flexibility Profiles of EV Users for Optimization of Ancillary Service Provision and Charging with Electric Vehicles

Panagiotis Tsagkaroulis

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Individual Flexibility Profiles of EV Users for Optimization of Ancillary Service Provision and Charging with Electric Vehicles

Individuelle fleksibilitetsprofiler af elbilsbrugere til optimering af netydelser og opladning af elbiler

Panagiotis Tsagkaroulis (s172736)

Master Thesis, August 2019

Supervisors:

Mattia Marinelli, Associate Professor at Technical University of Denmark
Andreas Thingvad, PhD student at Technical University of Denmark
Kenta Suzuki, Researcher at Nissan Motor Corporation

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**Author:**
Panagiotis Tsagkaroulis (s172736)

**Supervisors:**
Mattia Marinelli, Associate Professor at the Electrical Engineering Department of Technical University of Denmark
Andreas Thingvad, PhD student at Technical University of Denmark
Kenta Suzuki, Researcher at Nissan Motor Corporation

**Department of Electrical Engineering:**
Centre for Electric Power and Energy (CEE), Technical University of Denmark
Elektrovej, Building 325, DK-2800 Kgs. Lyngby, Denmark
www.elektro.dtu.dk/cee
E-mail: cee@elektro.dtu.dk
Denmark
Tel: (+45) 45 25 35 00

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Preface

This MSc thesis is prepared at the Department of Electrical Engineering (DTU Elektro) of the Technical University of Denmark (DTU), in fulfillment of the requirements for acquiring a Master of Science in Sustainable Energy at the Technical University of Denmark.

Under the supervision of Mattia Marinelli, Andreas Thingvad and Kenta Suzuki, this work has been carried out between February and August 2019.

The context of this thesis is recited as 35 ECTS for the Master of Science in Sustainable Energy.

Lyngby, August 9, 2019
Acknowledgements

This work is the conclusion of a journey started two years ago. Thus, I will grasp the opportunity to express my gratitude to all who contributed to it.

Firstly, I would like to pay tribute to my thesis supervisors Mattia Marinelli, Andreas Thingvad and Kenta Suzuki who were supportive and guided me through my MSc thesis during the past six months. Specifically, Mattia and Andreas who introduced me to this thesis and gave me their insights to make it happen.

Additionally, I want to thank my friends in Greece but also the ones I met around the world, for their endorse and all the moments we shared together. A special shout-out goes to my friends Amos and Nuri for their Ph.D admissions.

Finally, I would like to thank my family, especially my mother and my father for their unconditional support and belief in me, but also my grandfather whose guidance shaped a part of my character.
Abstract

The penetration of renewable energy sources in the power system, increases the share of intermittent resources, such as wind, solar etc. As a result the power balancing between supply and demand becomes more challenging. Additionally the transition of the energy consumption to electricity, in many sectors such as district heating with the use of heat pumps or transportation sector with the use of electric vehicles (EVs), is faced as a supplementary load by grid operators.

The on-going development on the EV batteries follows an increase on the storage capacity accompanied with a decrease in cost. Based on these, EVs can be treated as flexible and large storage units. With the use of bidirectional power chargers EVs could connected to the grid and provide frequency ancillary services, that would aid the power balancing of the grid but also bring additional revenue for the EV owners. This concept is called Vehicle-to-Grid (V2G) and allows the possibility of fast frequency response that contributes on the power system’s stability. EVs can provide frequency-controlled normal operation reserve (FCR-N) and ensure that the equilibrium between production and consumption is restored. With the proper strategy they could also participate in the electricity market and make profit by charging when the prices are low.

FCR-N is traded the day-ahead, thus it requires to schedule the service provision the day before. The main scope of this thesis is to formulate a schedule that maximizes the yearly revenue from service provision, for the EV owners. At the same time, a set of constraints should be respected, like the State of Charge (SOC) limits and the driving user behavior. By not respecting the SOC limits the EV’s battery will be depleted and as a result the EV will not be able to provide reliable services. Additionally, the losses of the power converter must be taken into account since they affect the energy of the battery. A data set consists of one year of system frequency measurements from the Nordic grid is used, in order to evaluate the effect of the frequency content of the system.

A set of telematics data is acquired, with all driving and charging occurrences of 7,163 Nissan 24 kWh LEAFs in the United States (U.S). The data set is without personal identification details but shows the daily behavior of each EV by itself during one year period. From the driving and charging pattern during one year, it is possible to calculate the value of potential grid services of each EV user individually but also as an average group value. It is assumed that every EV user has its own software agent that with some uncertainty can predict when and how far the user will be driving the following day. It is necessary to predict the availability the day ahead when the primary regulation market closes and it can be done based on a combination of the historical behavior and user input. The agent will then commit the EV for frequency regulation when it is neither being driven or being charged for the next drive. All of the individual agent’s bids will be added together to a combined bid to the TSO, and are assumed to be above the minimum bid size. The EV agent will predict what consumption from driving that is expected in the future and must make sure that the SOC is high enough before the departure. Amongst the conclusions, the very objective of this thesis is the evaluation of the yearly revenue of each EV owner, for the frequency response is delivered.
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Nomenclature

$\Delta E$ Energy exchange

$\eta$ Efficiency of the charger

$\lambda$ Spot price

$AC$ Alternative Current

$BRP$ Balance Responsible Party

$c$ Regulation price in Optimization

$DC$ Direct Current

$DSO$ Distribution system operator

$E_t$ Accumulated energy

$E_{bat}$ Energy in the battery

$E_{bias}$ Energy when frequency is biased

$E_{cont}$ Energy content

$E_{grid}$ Energy on the grid side

$EV$ Electric Vehicle

$FCR - N$ Frequency-Controlled Normal Operation Reserve

$h$ Length of periods in hours

$I$ Time horizon in optimization

$i$ Time step in optimization

$j$ Number Id for EVs

$max$ Maximum

$mean$ Average

$min$ Minimum

$n$ Hourly time step
$N_h$  Number of hour samples

$N_p$  Number of period samples

$P_c$  Power for charging

$P_d$  Power for discharging

$P_r$  Regulation power in optimization

$P_t$  Power at time $t$

$P_{cap}$  Charger’s nominal capacity

$P_{cor}$  Power for correction

$P_{nom}$  Charger’s nominal capacity in optimization

$p_{reg}$  Price for FCR-N

$Q_n$  Nominal capacity of the battery

$RES$  Renewable Energy Sources

$SOC$  State of Charge

$t_i$  Time step every 15 minutes

$y_t$  Frequency normalised response
1 Introduction

1.1 Motivation

A growing environmental awareness mainly drives to an increase in the share of renewable energy resources in the power grid, and it makes the power balance harder to maintain because the production is more fluctuating as it depends more on intermittent resources[1]. At the same time, the attempt to reach the ambitious environmental targets leads in the transition of energy consumption to electricity, which among others covers the electrification of domestic heating and the transportation sector.

The electrification of the transportation sector is caused by an increasing use of electric vehicles (EVs), which are seen as an additional load by the grid operators, as each EV doubles an average household’s electricity consumption. However, EVs can be a useful asset in the future power system because instead of passively consuming power they can provide valuable services to the power system as they are continuously manufactured with larger storage capacity and with the right power converter can provide a fast power response. The use of EVs for providing ancillary services to the power system can be both an additional revenue for EV owners and assist the integration of a larger share of RES.

Additionally, the EVs can participate in the electricity markets in order to decrease their charging costs by consuming energy when prices are lower. The use of bidirectional power converters instead of unidirectional, can substantially increase the capabilities and profitability of EVs, since they are able to offer power to the grid, a concept referred to as Vehicle-to-Grid (V2G). Bidirectional V2G can result in a higher profit compared to unidirectional case, however the profitability depends on many parameters such as the market electricity prices, plug-in hours, installation limit of the charger etc.

The integration of the vehicle to the grid is seeking to fully utilise EVs as both flexible demand and grid-connected batteries. According to this idea, EVs can provide frequency control by either modulating their charging or with V2G. The frequency reserve is traded in the day ahead market so it is necessary to schedule the service provision a day prior. The schedule for charging and service provision can be made with respect to the energy and reserve prices to achieve the maximum profit. The scope of this thesis is to form a plan that optimizes the revenue of each EV owner while respecting all constraints, such as physical storage capacity and user requirements, in order for the EV to be able to provide reliable services.
1.2 Background

1.2.1 Global warming of 1.5°C and the relation with greenhouse gas emissions

The result of human activities on earth, are the greenhouse gas emissions (GHGs). The concentration of atmospheric carbon dioxide (CO$_2$) has increased over the last decades as a result of the burning of fossil fuels like coal and oil. GHGs trap heat and make the planet warmer. In the decade 2006–2015, global temperature reached +0.87°C ($\pm$0.12°C) relative to 1850–1900, predominantly due to human activity increasing the amount of greenhouse gases in the atmosphere. Given that global temperature is currently rising by 0.2°C ($\pm$0.1°C) per decade, human-induced warming reached 1°C above pre-industrial levels around 2017 and, if this pace of warming continues, will reach 1.5°C between 2030 and 2052.

Under the 2015 Paris Agreement, most countries agreed to cut GHGs ‘holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels’.

Fig. 1 shows that the human-induced warming reached approximately 1°C above pre-industrial levels in 2017. At the present rate, global temperatures would reach 1.5°C around 2040. Stylized 1.5°C pathway shown here involves emission reductions beginning immediately, and CO$_2$ emissions reaching zero by 2055[1].

Figure 1: Cumulative emissions of CO$_2$ and future non-CO$_2$ determine the probability of limiting warming to 1.5°C [1]

A more precise definition of what is meant by ‘global average temperature’, but also many more definitions, can be found in the References, in the special climate report made by Intergovernmental Panel on Climate Change (IPCC), which covers the topic on impacts of global warming
of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways [2].

1.2.2 Global greenhouse gas emissions by economic sector

The man-made participation of the greenhouse effect is caused by man’s activities that emit greenhouse gases to the atmosphere. The most important of these is the burning of fossil fuels. To a lesser extent, the clearing of land for agriculture, industry, and other human activities has increased concentrations of greenhouse gases. Fig 2 depicts an overview of the CO₂ emissions by economic sector, based on another report of IPCC[3].

![Figure 2: Global Emissions by Economic Sector](image)

The largest source of GHGs occurs from the electricity and heat production. The main cause is the burning of coal, natural gas and oil, which produce high emissions per energy unit. While at the same time, electricity could be produced from renewable energy sources with grams of CO₂ per kWh close to zero. By doing so, the energy consumption remains the same but with significantly less emissions per kWh.

In the same way, the remaining sectors that produce GHGs could also be more CO₂ neutral by converting to electricity that comes from clean energy sources. An example has been made in the buildings sector where the domestic air and water heating is produced by heat pumps, which can become more efficient and less CO₂ polluted, where electricity was produced from renewables. In the transportation sector almost all (95%) of the world’s transportation energy comes from petroleum-based fuels. However, the transition from fossil fuelled internal combustion engines (ICE) vehicles to EVs is ongoing. A strengthening tide of industry initiatives and policy support leads to a projection for the global EV fleet up to 280 million by 2040, from 2 million today according to the International Energy Agency (IEA). Therefore the conversion into electricity as the main energy source, which makes it possible to achieve an overall reduction in CO₂ emissions.

The IEA predicts that the electricity consumption will increased significantly among worldwide end-users of energy, making up 40% of the rise in final consumption to 2040.
Electricity makes inroads in supplying heat and mobility, alongside growth in its traditional domains, allowing its share of final consumption to rise to nearly a quarter.[4]

Specifically in Denmark, the Danish Transmission System Operator (TSO), Energinet predicts that the Danish electricity consumption will increase significantly because of the electrification of other sectors such as transportation, building heating but also the railway network. Energinet’s prediction is shown in Fig.4 which shows the expected trends, from new sectors[5].

1.2.3 Electricity generation from renewable sources

The primary production of renewable energies is on a long-term increasing trend, that is actively ongoing around the world. In Europe, between 1990 and 2015 it increased by 203 % (an
average annual growth rate of 8.12% relative to 1990). In 2015, renewable electricity generation accounted for 29% of total gross electricity generation[6]. The renewables share on the electricity generation increased by 4.0% in 2015 compared with 2014. However, the picture varies depending on the energy source. From a decrease of 9.0% for electricity generation from hydro to a 19.3% increase for wind power, as it can be observed in the following Fig.5 between 1990 and 2015. Hydropower plants generate the largest share of electricity from renewable energy sources in Europe, since it’s a very reliable and controllable source of energy, which can be used based on the demand. At the same time, this source of energy can be installed in specific sites with high altitude and large water reservoirs, for this reason it has limited potentials of increase in the upcoming future.

A more rapid expansion of electricity generation from other renewable sources, such as wind power and solar power generation has been observed over the period 2005-2015. This trend is due to the technological progress, which makes them more efficient and at the same time cheaper sources of electricity. However, they are both based on intermittent energy sources as they depend on sun and wind and that makes them uncontrollable. Despite their uncertainty, wind power share managed to grow significantly the last decade. Other renewables such as, solid biomass and wood are also used in conventional thermal generation power plants and they keep on increasing, however with a slower pace. The use of biomass is limited since it is strongly depend on the source of the fuel. In example if the fuel needs to be transferred from a distant place, that might be not too profitable or environmental friendly. An overview of the electricity generation from renewable sources is shown in Fig. 5, where the electricity production is not normalized in the area chart but the dashed line shows the total normalized electricity generation, which makes obvious that there is a steep increase of the renewable sources after 2005.
Moreover, an energy source that is also CO₂ neutral, even more than biomass is nuclear power. However, this graph doesn’t represent the levels of the installed nuclear power plants in Europe.

### 1.2.4 Greenhouse gas emission potential

The emission intensity of electricity production, measured in gr. CO₂/kWh, can be used as a measure to compare the specific GHGs of suggested emission mitigation options and those of conventional power supply technologies. In Table 1, the median life time emissions of the different technologies presented in the IPCC 2014 report, are taken into consideration[7].

<table>
<thead>
<tr>
<th>Technology</th>
<th>CO₂/kWh</th>
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<tbody>
<tr>
<td>Coal</td>
<td>820 gr.</td>
</tr>
<tr>
<td>Gas</td>
<td>490 gr.</td>
</tr>
<tr>
<td>Biomass</td>
<td>230 gr.</td>
</tr>
<tr>
<td>Solar PV - Utility scale</td>
<td>48 gr.</td>
</tr>
<tr>
<td>Solar PV - rooftop</td>
<td>41 gr.</td>
</tr>
<tr>
<td>Concentrated solar power</td>
<td>27 gr.</td>
</tr>
<tr>
<td>Geothermal</td>
<td>38 gr.</td>
</tr>
<tr>
<td>Hydropower</td>
<td>24 gr.</td>
</tr>
<tr>
<td>Wind Offshore</td>
<td>12 gr.</td>
</tr>
<tr>
<td>Wind Onshore</td>
<td>11 gr.</td>
</tr>
<tr>
<td>Nuclear</td>
<td>12 gr.</td>
</tr>
</tbody>
</table>

Table 1: Life cycle CO₂ equivalent from selected electricity supply sources.

As it can be seen, the difference on the emission between the conventional fossil fueled electricity sources and the renewable energy sources is significant. Worth-mentioning is that nuclear power has also low emission intensity, however it requires high construction investment with many requirements regarding the management of nuclear waste, but also generates external dependence since not many countries have uranium mines[8]. The conclusion here is that if the generation is shifted from the conventional power sources to renewable energy sources the CO₂ will be decreased substantially.

### 1.3 Electricity generation in Denmark and Great Britain (GB)

In this section the electricity generation in Denmark and GB will be described since this thesis is focusing on Denmark’s and GB’s power system.

Denmark is among the countries with the highest share of generated electricity based on renewables and wind power is one of the most widespread kinds of renewable energy. Fig[9] shows the share of electricity generation based on renewables in 2017[9].
As it can be seen from Fig. 6, wind power owns the highest share of electricity generation produced from renewables, with 66%. The electricity generation from solid biofuels comes next with 22%, while the electricity generation from other renewable energy sources has only 8% of the total share. All other renewables include electricity generation from gaseous and liquid biofuels, renewable municipal waste, geothermal, and tide, wave ocean.

The remaining percentage is shared by solar and hydro power and it is barely 5%. The main reason is the low solar radiation and the flat terrain of the country.

Fig. 7 shows the total consumption and production within a 7-day period, in Denmark, from 2019.3.7 to 2019.3.13. The Danish grid consists of two interconnected grids. Western Denmark (DK-1) is connected to the European continent synchronous grid and Eastern Denmark (DK-2) is connected to the Nordic synchronous grid, which includes Denmark, Sweden, Norway and Finland. As a consequence DK1 operates according to the ENTSO-E Continental Europe Operation Handbook legislation, whereas DK2 follows the Joint Nordic System Operation Agreement. As it can be observed, some days the production exceeds the consumption and
some others it is the other way around. However, since Denmark is split in two grids, it’s not very accurate to talk about balance between consumption and production on national level. Energinet as the national Transmission system operator (TSO) and an independent public entity, has the role to maintain and to operate the national power grid, by ensuring security of supply, using activities such as Ancillary Services [11].

The electricity generation in GB is depicted, in the following Fig.8. Once again wind power is the dominant source of electricity from renewables. However, this dominance is represented by a lower percentage of 49%. In the second place it comes the generation from solid biofuels with 21%, while hydro possesses the last position with only 6%, once again. The rest of the share is split evenly among solar and other renewables with 21%.

![Electricity generation in GB (ktoe), 2017](image)

Figure 8: Projections of generation and net imports in GB by technology group [9].

Currently GB’s electricity market currently has 4GW of interconnector capacity:

- 2GW to France (IFA)
- 1GW to the Netherlands (BritNed)
- 500MW to Northern Ireland (Moyle)
- 500MW to the Republic of Ireland (East West).

There are currently three TSOs permitted to develop, operate and maintain a high voltage system within their own distinct onshore transmission areas in GB. These are National Grid Electricity Transmission (NGET) for England and Wales, Scottish Power Transmission Limited for southern Scotland and Scottish Hydro Electric Transmission for northern Scotland and the Scottish islands groups.
1.3.1 Effect of replacement of conventional vehicles with electric vehicles in the transport sector

When it comes to a comparison between EVs and Internal Combustion Engine (ICE) vehicles, there is a wide spectrum of differences to think of, such as the energy efficiency and the cost, which mainly depends on the region. In general EVs are preferred compared to ICE vehicles in terms of energy efficiency. In terms of CO$_2$ emission EVs have the upper hand compared to ICE vehicles, even if the mix of electricity that is used is not entirely produced by renewables. Based on the vehicle characteristics, most of the ICE vehicles require 0.63 kWh/km while EVs use approx. 0.2 kWh/km\textsuperscript{[12]}. The calculations are based on the assumption that the energy comes from the battery without taking into consideration the energy efficiency losses when charging from the grid\textsuperscript{[13]}. According to Energinet’s environmental report, the average value of CO$_2$ emissions in Denmark was 194 gr./kWh in 2017, including the transmission grid losses, transit losses from international connections are also included\textsuperscript{[14]}. The CO$_2$ emissions vary among the countries since they are strongly dependant on the supply mix of the electricity production.

Consequently an EV emits:

\[
0.2 \text{ kWh/km} \cdot 194 \text{ gr./kWh} = 38.8 \text{ gr./km} \tag{1}
\]

The average CO$_2$ emission rate for diesel used as a fuel for an ICE vehicle is 121.5 gr./km \textsuperscript{[15]}, the value represents combined city and highway fuel economy.

The average electricity price of 2.3 DKK/kWh \textsuperscript{[16]} is used to calculate the driving price of EVs. It is the electricity price for households the first half of 2018, in Denmark.

\[
\frac{2.3 \text{ DKK/kWh}}{5 \text{ km/kWh}} = 0.46 \text{ DKK/km} \tag{2}
\]

The fuel consumption for an ICE vehicle is 10.75 l/km\textsuperscript{[15]}. While the average gasoline price is 11 DKK/l.

Based on these:

\[
\frac{11 \text{ DKK/l}}{10.75 \text{ l/km}} = 1.02 \text{ DKK/km} \tag{3}
\]

The comparison between EVs and ICE vehicles when it comes to emitted CO$_2$ emissions and driving cost are seen on Table\textsuperscript{2}.

<table>
<thead>
<tr>
<th></th>
<th>EV</th>
<th>ICE vehicle</th>
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<tbody>
<tr>
<td>CO$_2$/km</td>
<td>38.8 gr./km</td>
<td>121.5 gr./km</td>
</tr>
<tr>
<td>Cost/km</td>
<td>0.46 DKK/km</td>
<td>1.02 DKK/km</td>
</tr>
</tbody>
</table>

Table 2: Comparison between two different indicators.
A brief summary of the results from Table 2 gives the impression that the use of EVs is a cheaper solution compared to ICE vehicles in Denmark. The additional cost of the applied taxes on electricity, was taken into consideration. The fact that the price of electricity decreases every year, increases the incentive for electrification of the transport sector. For this reason, EV charging, on the domestic level is becoming more popular in Denmark.
1.4 Thesis description

This thesis examines to what extent an EV can support the stability of the power grid by procuring frequency regulation services, with main focus on calculating the potential revenue of these services in the Danish market. This includes an assessment of the Nordic power system’s frequency bias and the relation of the efficiency losses during service provision. An economic evaluation of the reserve and spot market prices is also essential along with a statistical analysis on a large amount of EV driving data. Finally, an optimal schedule that calculates the yearly revenue while respecting various set of constraints is calculated.

The learning objectives can be summarized in the following questions:

- What is the effect of the biased frequency and the efficiency losses on service provision with EVs?
- Is the utilization of an EV as a single unit or an EV fleet for FCR-N provision in the Danish market under the Transmission System Operator profitable?
- Is it possible to estimate the availability of the EVs for service provision but also the frequency regulation prices when they are not known?
- Can an optimized charging and service provision schedule that respects a set of physical constraints, result in higher revenue for the EV owner?

1.5 Thesis outline

- **Chapter 2**: This chapter gives an overview of the power system as well as the power market structure. Furthermore, the ancillary services both in Denmark and GB are described.

- **Chapter 3**: Contains an analysis on US EV driving data from Nissan and a comparison with the Danish national transport data.

- **Chapter 4**: A statistical analysis on the system’s frequency in Denmark in addition to the effect of the efficiency losses in the energy content both in Denmark and GB is examined.

- **Chapter 5**: In this chapter a holistic model that calculates the revenue from service provision is made. In an analytical manner, the first part of this chapter deals with the calculation of the charging and service provision schedule but also the formulation of the SOC correction. Afterwards, the capacity payment method related with the service provision is described, both in Denmark and GB. In continuation the final results are presented. Finally an estimation of the EV availability and the prices for frequency regulation follows.

- **Chapter 6**: An optimization model that schedules the charging and service provision in order to maximize the revenue while respecting a set of constraints is used.

- **Chapter 7**: In this chapter the conclusions and future work are contained.
2 An overview of the power system

2.1 Power system frequency

An electric power system is a system where power is produced, transmitted and consumed in real time. Power is irregular and produced according to the demand. The electrical grid consists of a high voltage transmission network for the purpose of reducing the losses while transmitting the power over long distances. The voltage magnitude is reduced, when it reaches close to the consumers, by medium or low voltage transformers. A balance between production and consumption of electricity must always be maintained in a power system. The responsible entity for the power balance in a system, is the Transmission System Operator. A change in this balance alters the system frequency and if this violates a strictly predefined frequency range, it can threaten the stability and thus the security of the power system[17].

Power systems are based on alternating current (AC) applications. An alternating current occurs typically when the voltage source (i.e. potential energy source) alternates around zero with an average value over a period $T$, see Fig.9.

![Figure 9: Alternating signal](image)

The time in seconds it takes the signal to complete one cycle is called a period (revolution), denoted typically by $T$. As indicated in Fig.9 the frequency $f$ is the term used to describe the number of cycles of an alternative signal in a second, with the unit hertz(Hz). The synchronous electrical angular speed $\omega$ is defined as:

$$\omega = 2 \cdot \pi \cdot f \ (\text{rad/s})$$

Where $f$ denotes the synchronous frequency. The calculation of $\omega$ required the conversion from Hz to rad/s.

Synchronous region is defined as a regional power system that operates at a synchronized frequency and it is tied together during normal system operations. All the grids in Europe are AC connected grids. Their frequency is synchronized within the grid and they operate at 50
Hz, while those in USA operate at 60Hz. There are five synchronous regions existing in the European Network of Transmission System Operators for Electricity (ENTSO-E):

- Continental Europe synchronous grid
- Ireland’s synchronous grid
- United Kingdom’s synchronous grid
- Nordic synchronous grid
- Baltic synchronous grid

The main task of ENTSO-E is to maintain the frequencies in all five synchronous power systems balanced around the standard nominal value of 50 Hz ensuring a safe European power supply. Frequency in the power system is directly related to the rotating speed of the synchronous generators connected to the system. The frequency is synchronous all over the system, when the systems operate normally but small deviations can happen locally as a result of the oscillations of the synchronous machines.

### 2.2 Power system balancing with frequency control

Generating units transform other sources of energy in the process of producing electrical energy. For example hydraulic, heat, solar, wind sources of energy can be used in the production of electrical energy. The generator is driven by a prime mover, which can be for example a steam, gas or hydro turbine. From the viewpoint of frequency control, the power system can be thought as one large power plant supplying one load. Two opposite torques act on the large rotating mass, namely a mechanical torque $T_{mec}$, which is the sum of all the prime movers and an electrical torque $T_{elec}$, which is the sum of all the loads. In case of an imbalance between these torques, the rotating mass will experience an angular acceleration or deceleration $d\omega/dt$:

$$T_{mec} - T_{elec} = I \cdot \frac{d\omega}{dt} \ (kg \cdot m^2/s^2) \ (5)$$

where $I$ is the moment of inertia of the rotational mass. Notice that the inertia $I$ has a stabilization effect, i.e. in case of an imbalance in torques, the frequency change is slower for a system with high inertia compared to a system with low inertia, because the time of response is higher, however, the deviation of the frequency will be the same. As a result a high inertia system is more stable compared to a low inertia system.

Eq.5 is also known as equation of motion (EoM). The EoM includes generally rotating components of the power system i.e. generating units and loads. A sudden increase in all production, namely in $T_{mec}$, implies an increase in the frequency. On the other hand, an increase in the consumption, namely in the $T_{elec}$, implies a decrease in the frequency. It is worth noticing that the larger the inertia of the rotating mass is, the smaller the speed rate-of-change following a torque imbalance is.
The EoM can also be expressed in power terms by using the proportional relationship between power and torque:

\[ P = T \cdot \omega \quad (kg \cdot m^2/s^2) \]  

(6)

By applying Eq.6, the equation of motion in power terms, can be expressed as:

\[ P_{mec} - P_{elec} = I \cdot \omega \cdot \frac{d\omega}{dt} \]

(7)

Eq.7, which is the power balance equation, shows that as long as there is a power imbalance, the \( \omega \) will continue to deviate as the derivative will be different from zero and as a consequence the frequency of the system will deviate along with it. Thus a frequency measurement can point out whether there is an imbalance or not.

As the inertia of the modern systems is getting lower with the increased penetration of renewables, a faster time of response is required, in order to protect the generators and establish stability to the grid by not losing the synchronism between them.

### 2.3 Structure of the power market

The Nordic countries, Norway, Sweden, Finland and Denmark, deregulated their power markets in the early 1990s and brought their individual markets together into a common Nordic market, the Nord Pool Spot A/S. Estonia, Latvia and Lithuania deregulated their power markets, and joined the Nord Pool market in 2010-2013. The term ‘deregulation’ means that the state is no longer running the power market, and instead free competition is introduced[18].

When the electricity market is liberalized, electricity becomes a commodity, like oil. In the beginning, there is, a wholesale market and a retail market and there are the three usual players, the producers, the retailers and the end users. However, for electricity a more advanced pattern is developed.

In a liberalized power market, the retailers act as intermittent between the end users and the producers. The retailers buy the energy and then sell it to the end users. Thus the end users or consumers, have the option to choose between different retailers, based on the lowest price.

In a power market, the producers who produce energy with the lowest price, will be preferred. The retailers with the lowest bid, will be able to sell their energy, to the consumers, while at the same time will try to maximize their profit.

The TSO is an entity, responsible for ensuring that the system remains stable and the supply and demand is in balance the whole time, as seen in section 2.1. The TSO must be a non-commercial and neutral organization. In Denmark, the TSO is the state-owned grid company Energinet.

Nord Pool is a common Nordic marketplace for energy trading and is responsible for the forward market, while the ancillary services market, is under the jurisdiction of Energinet. In the forward market future contracts for delivery of electricity further in the future are traded along with contracts which price deliveries.

The participants on the market that are responsible for the imbalances between production and consumption by buying and selling electricity when it is necessary, are called balance responsible
parties (BRPs).
A more detailed description is presented below.

- **Bilateral contracts:** These are energy contracts that are settled long before the time of operation, it can be months or years ahead. Prices in the forward market are used as a basis for pricing a fixed-price contract with a customer.

- **Day-ahead market, or Elspot** is run the day before the date of actual power transfer. The BRPs buy and sell electricity at Nord Pool Spot on behalf of electricity suppliers and plant owners, on an hourly basis. They submit plans to Energinet.dk, on the electricity expected to be generated and consumed in the next 24 hours. The market is settled at noon the day ahead.

- **Intra-day market, or Elbas** is continuous, and power trading takes place until 1 hour before the power is delivered. The intra-day market supplements day-ahead market, by providing the necessary balance between supply and demand. Renewable energy producers that can have difficulties forecasting their production since RES are less controllable compared to conventional power plants, can participate in this market to minimize their losses.

The parties who are responsible to maintain the hourly balance are the BRPs and upon entering an agreement with the TSO they are financially liable for the imbalances that they cause. Imbalances describe operational schedules which are not in line with energy plans. In case where the energy is not delivered as promised on the forward agreements, the TSO impose a penalty. The goal of BRPs is to optimize their profit while respecting the TSO’s requirements. In case of an excess in the demand the TSO will have to sell energy to the BRPs. This amount of energy will be sold in the down regulation price which is always equal or lower to the spot market price. On the other hand in case of under production the TSO will have to buy energy form the BRPs in the up regulation price, which is always equal or higher than the spot price.
2.4 Ancillary Services

The conventional generators result in a higher inertia of the power system compared to the renewable energy sources (RES), however they are harmful for the environment. For this reason, aggregation on the demand side of controllable devices to perform frequency control is a good solution to alleviate the expanding need in response time. Some of those controllable devices, have no rotational inertia and are connected to the grid via power electronics. Thus, with a well coordinated control we can achieve a significant improvement to the stability of the system’s frequency. The challenge is associated with the control of large distributed loads, such as electric vehicles (EVs), residential battery energy storage systems (BESSs), water heaters\[20\].

BESSs are among key factors for the future and they present a fast dynamic response to compensate the load variations in distribution networks. Lithium-ion batteries are fast growing, and are expected to be dominant in the near future\[21\]. Also, the combination of residential and non-residential BESS with photovoltaics (PV) systems, are growing up day by day due to the technical developments and cost reduction of PV systems. However Lithium-ion batteries, still face high production cost compared to other batteries and solar PVs are considered an uncontrollable power source, which can compromise their availability.

Electric boilers are ideal home appliances, since they are controllable in terms of frequency regulation, by turning On and Off the device in response to a pre-defined value of frequency deviation\[21\]. The two main types of electric water heaters are those with the electric resistance and the heat pump water heater. The main difference in the way they function, lies in the fact the that heat pump water heater, works with a compressor. For this reason when the temperature reaches the desired value, the compressor goes Off and it requires several minutes to be On again, which limits the availability of the device. In contrast, the electric resistance heater can be switched On and Off at any time, however the power required to operate them is higher than any other home appliances\[20\].

The increasing penetration of EVs is an on-going project, across the world, with an overall annual production of EVs, over 100 million by 2050\[20\]. Their integration is about to play a significant role in the transportation sector. However, when they are not being driven, they can be used as a provision of frequency response service to the grid. Also, with the use of a bidirectional charger their ability to provide demand response for frequency regulation, is extended, since they can deliver power to the grid. In this specific scenario, the EV owner, is getting paid for providing availability services to the grid. Experimental level, it is validated that series-produced EVs, can be a source of frequency regulation procurement\[22\].

2.5 Frequency regulation in Denmark

In any power system, a balance must be struck at all times between the production and the consumption of electricity. A set point of 50 Hz has been set, and a deviation from this value, indicates the power imbalances that might have arisen. Thus frequency is an indicator to measure the imbalances and it is the role of the primary reserve to restore the balance between
the production and consumption. A power system consists of different response mechanisms, however the primary frequency control is the subject of examination here.

Requirements to be met by suppliers of ancillary services vary slightly depending on whether the services are to be supplied in Eastern Denmark (DK2) or in Western Denmark (DK1). DK2 is a part of the Regional Group Nordic (RG-N) and Energinet, as the danish TSO is responsible to supply the frequency normal operation reserve and FCR-N is the most fitting reserve for EVs, as the EV both would charge and discharge, depending on the frequency, and thereby use the battery as a temporary storage than a source of production. Further explanation will be given for DK2 system as it is the scope of this thesis.

The ancillary services which are procured from electricity generators and electricity consumers in Denmark and in neighbouring countries are used for various purposes, and different requirements therefore apply to the supply of the various services. These requirements are regulated by the ENTSO-E Continental Europe Operation Handbook, the Joint Nordic System Operation Agreement and by Energinet’s regulations for grid connection. PFC is divided into two services, Frequency Normal Operation Reserve (FCR-N), is used for continuous imbalances and is activated for all system frequency deviations within a range of $\pm 100$ mHz. In conjunction with a rapid frequency change to 49.9/50.1 Hz, FCR-N shall be up regulated/down regulated within 150 seconds. Frequency Disturbance Operation Reserve (FCR-D), is used in upward directions situations, when frequency goes below 49.9 Hz. The purpose of FCR-D is to mitigate the impact of incidental disturbances[23].

In the case of a frequency deviation, the purpose of FCR-N is to re-establish an equilibrium between production and consumption. The combined requirement in the ENTSO-E RG Nordic grid is 600 MW, of which Energinet.dk is obliged to supply a proportionate share. Energinet.dk procures the FNR through daily auctions in collaboration with Svenska Kraftnät. The requirement is published on Energinet’s website. Energinet’s requirement is 23 MW, while Svenska Kraftnät’s requirement is 230 MW [24]. The service can only be provided by a Balance Responsible Party (BRP) with a minimum bid size of 0.3 MW. FNR is a service offered for both upward and downward regulation, thus the responsible party must provide the same amount of power for up- and down regulation. The reserve must as a minimum be supplied linearly at frequency deviations of between $\pm 100$ mHz, while for disturbances that exceed these limits the activation should be full. The activated reserve must be supplied within 2-3 minutes, regardless of the size of the deviation.

For a frequency value $f_t$ at time $t$, the normalized response $y_t$ is calculated as:

\[
y_t = \begin{cases} 
-1, & \text{if } f_t < 49.9 \text{ Hz} \\
(f_t - 50)/0.1, & \text{if } 49.9 \text{ Hz} \leq f_t \leq 50.01 \text{ Hz} \\
1, & \text{if } f_t > 50.1 \text{ Hz}
\end{cases}
\]  

(8)

The provision of frequency-controlled normal operation reserve (FCR-N), is made by implementing the droop control technique, which determines set points for the normalized response
on the grid side, by correlating linearly the frequency deviations with the normalized response. The following Fig.10 shows the behavior of the normalized response. A negative normalized response ($y_t$) signifies under frequency, thus the available unit supplies power to the grid, while a positive value indicates that there is an over frequency, as a result the power flows from grid to the unit. FCR-N is paid for the available power ($P_{cap}$) per hour.

![Droop control characteristic](image)

**Figure 10: Droop control characteristic**

The power required each time ($t$), is a result of the the multiplied normalized response with the available power capacity.

$$P_t = P_{cap} \cdot y_t + P_{base}$$  \hspace{1cm} (9)

Energinet’s and Svenska Kraftnät’s total requirement (253 MW in 2017) is procured on daily basis where a part of it is procured two days before the day of operation and the remaining part is procured the day before.

As a principle, bids for FCR-N are always sorted according to the price/MW, and Energinet’s and Svenska Kraftnät’s share obligation is covered by selecting the lowest bids. All accepted bids, receive an availability payment according to the ‘pay-as-bid’ mechanism [25].

Since the players only know their own bid, it is not certain if they will be accepted or not and although higher bids might reflect in more revenue there is no guarantee that all the bids will be accepted. The prices vary according the the supply of the service, thus the price is higher in certain periods. This is because fewer power plants operate during certain hours. The following
Fig. 11 shows the availability price every hour for a whole month during May 2018 in €/kW. As it can be seen, the payment is generally higher during morning hours (from 00:00 until 07:00), with a large variance between the single days. However, after 10:00 the variance of the price is significantly low, around 0.02 - 0.005 €/kW.

Figure 11: FCR-N price per hour, during May 2018

Fig. 12 shows the average value of FCR-N price per hour during three different years. Since the prices during 2018 are considered to be unrealistic high, the prices during 2017 will be used for the calculation of the revenue from FCR-N procurement in the following chapters.

Figure 12: The average value of FCR-N price per hour, for 2016, 2017 and 2018.

In addition, with the day-ahead settling, where the TSO buys capacity from the BRPs, there is a different payment that is settled every hour. If the average frequency within an hour is above
or below 50 Hz there is an energy exchange between the BRPs and the grid, in that case the system’s frequency carries an energy content \( E_{\text{cont}}^h \), or there is an energy bias \[26\]. If energy is supplied to the grid the energy content is negative \( E_{\text{cont}}^h < 0 \), thus there is under frequency, and the payment for the energy that has delivered is settled, with the upward regulation price. On the other hand, if energy flows from the grid, the energy content is positive \( E_{\text{cont}}^h > 0 \), thus there is over frequency, and the energy received is settled with the downward regulation price.

The different kind of payments are depicted in Fig.14.

![Diagram showing the different payments between BRP and TSO for FCR-N service.](image)

**Figure 14:** The different payments between BRP and TSO for FCR-N service.

Fig.15 shows the spot price, the up- and down regulation price during a week. As it can be seen, the prices for upwards and downwards regulation are favorable for the BRP since the up regulation prices are most of the time equal or higher compared to the spot prices and the down regulation prices are equal or lower than the spot prices, thus the BRP will receive the energy back in a favorable price. When the TSO is forced to exchange energy, due to frequency fluctuations, most of the times the responsible parties will make profit out of it.

![Graph showing spot, up, and down regulation power prices in DK-2, February 2-8, 2018.](image)

**Figure 15:** Spot (green line), up- (blue line) and down (yellow line) regulation power price in DK-2, Friday February 2. to Thursday February, 8. 2018 \[27\].
2.5.1 Electricity prices for households including taxes

The Danish bill (DK2) of electricity for households is described. A Danish electricity bill includes both fixed terms and consumption-based terms [28]. A standard household, with an annual consumption of 4000 kWh [29], electricity bill, includes fixed terms and term that depend on the consumption. The household electricity bill for a 400V consumer consists of the following terms:

- The price for electricity (DKK/MWh)
- Network tariffs (DSO) (282 DKK/MWh), transport tariffs (TSO) (80 DKK/MWh)
- The Public Service Obligation (PSO) levy (149 DKK/MWh)
- Energy taxes (914 DKK/MWh)
- Value-added tax (VAT) applied to all previous terms (25%)
- and a subscription tax (708 DKK/y)

However, according to the current legislation, the electric vehicle charging is exempt from PSO levy and energy taxes. Therefore, in the final EV user bill the PSO levy and the subscription tax are not included. This leads to a reduced tariff equal to approximately 50% [30]. The final bill is calculated according to Eq. (10) based on the electricity supply fees, network tariffs, transport tariffs and VAT.

\[
\lambda_h = (\lambda_{Elspot}^h + tax_{DSO} + tax_{TSO}) \cdot (1 + VAT)
\]  

(10)

2.5.2 FCR-N vs Spot price

A comparison between the FCR-N and the spot prices is shown in the following figure. Fig. 16 shows the evolution of Spot and FCR-N prices, in 2017.
The low spot prices signify that there is a high production from renewables. Since the operation of RES has low marginal cost compared to the operation of thermal power plants, RES are scheduled first and as a result the conventional thermal power plants will not get paid for their production.

Fig. 17 shows the FCR-N prices during 2017 in Denmark. As it can be observed during the cold periods the prices are lower compare to the warmer periods, throughout the year. The operation of conventional power plants based on fossil fuels is costly. Apart from electricity production, thermal power plants also produce heat. Although in winter the operation of thermal power plants is essential, for the heat production, during Summer heat is not necessary therefore operating them solely for electricity production is not profitable.
2.6 Frequency regulation in GB

The National Grid Electricity System Operator (NGESO), is the TSO in GB. NGESO procures 3 GW of reserve, which is split in 1.5 GW Mandatory Frequency Response (MFR) and 1.5 GW Firm Frequency Response (FFR). MFR is delivered to the grid under bilateral agreements by balancing mechanisms. A balancing mechanism is a power plant that has made an agreement with NGESO to deliver regulating power. In the scenario that NGESO is expecting an under/over production it can accept a bid from a power plant, that has an agreement with the NG, to increase or decrease production. While there is a deadband of $\pm 0.015$Hz where response is not provided and the minimum capacity bid should be 10 MW, coming from a single or several units.

FFR is an open market service that also can be delivered by units that do not have a status of balancing mechanism. FFR acts as a supplementary resource on top of MFR and the amount varies depending on NG’s estimations but also the season and time of the day. While FFR’s minimum bid should be 1 MW.

Both MFR and FFR consist of three frequency regulation services, primary, secondary and high.

NGESO has a shared set of grid codes describing the different ancillary services with the purpose of maintaining system stability. Primary, secondary and high are dynamic services where the response should be proportional to the frequency deviations with the maximum power set at a deviation of either 0.2, 0.5 or 0.8 Hz. There are two options of delivering the services. The non-dynamic or static and the dynamic option. The idea of non-dynamic services is that an agreed amount of energy is delivered if the system frequency hits a certain trigger point. While the dynamic services is delivered according to the frequency deviations. In this case, the concept of dynamic services is examined.

The FFR in GB, consists of three response services:

In case of an under frequency:

- **Primary response** - Response provided within 10 seconds of an event, which can be sustained for a further 20 seconds.

- **Secondary response** - Response provided within 30 seconds of an event, which can be sustained for a further 30 minutes.

In case of an over frequency:

- **High frequency response** - Response provided within 10 seconds of an event, which can be sustained indefinitely.

Unlike Denmark, in GB there is a dead-band of $\pm 0.015$ Hz that signifies if there is a need to act as a result of an over or under-frequency.

Primary, secondary and high are dynamic frequency response services, which are continuously provided to manage the normal second-by-second changes on the system and the response should be proportional to the frequency deviations. Primary response should have a maximum power at a deviation of $[0.2, 0.5, 0.8]$ Hz, secondary should have a maximum response at $[0.2,$
0.5| Hz, while high response has a maximum power at a deviation of [0.2, 0.5] Hz, see Table 3. A combination of primary, secondary and high response, with a full response at ±0.2 Hz is considered.

<table>
<thead>
<tr>
<th>Response</th>
<th>Time</th>
<th>Duration</th>
<th>Max response at ± Hz deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>10 s</td>
<td>30 s</td>
<td>-0.2, -0.5, -0.8</td>
</tr>
<tr>
<td>Secondary</td>
<td>20 s</td>
<td>30 min</td>
<td>-0.2, -0.5</td>
</tr>
<tr>
<td>High</td>
<td>10 s</td>
<td>Indefinite</td>
<td>0.2, 0.5</td>
</tr>
</tbody>
</table>

Table 3: Characteristics of frequency regulation services

In GB a specific combination of service delivery is required, the possible service combinations are as follows:

- Primary and secondary
- Primary, secondary and high
- High only

For a frequency value ($f_t$) at time t, the normalized response ($y_t$) of the energy content is calculated:

$$y_t = \begin{cases} 
-1, & \text{if } f_t < 49.8 \text{ Hz} \\
(f_t - 50)/0.2, & \text{if } 49.8 \text{ Hz} \leq f_t \leq 49.985 \text{ Hz} \\
0, & \text{if } 49.985 \text{ Hz} \leq f_t \leq 50.015 \text{ Hz} \\
(f_t - 50)/0.2, & \text{if } 50.015 \text{ Hz} \leq f_t \leq 50.2 \text{ Hz} \\
1, & \text{if } f_t > 50.2 \text{ Hz} 
\end{cases}$$

(11)

While the power ($P_t$) required at time t, is calculated in the same way with Eq.9.

All the bids for the services for the upcoming month, must be submitted one month prior and more specifically until the first working day of that month, i.e 1st of January for services starting on 1st of February. Unlike the electricity market in Denmark, the contract periods in GB are based on the Electricity Forward Agreement (EFA). As a rule the delivery service is traded in six 4-hour blocks per day. Thus the participants are obliged to be available at least 4-hours, starting and ending, at specific times, see Table 4.
NGESO procures the amount of primary, secondary and high frequency response for the specific EFA blocks. The share of these services are bought per month, per four months and per six months.

There is a price range, depending on the volume of the traded service and the period. The TSO compiles a monthly report that states how much capacity was delivered at each price range.

The electricity price system in GB is more complicated and differs in every region. There are not hourly prices for frequency regulation but instead the accepted payment will be a result of a combined bid. In this model it is assumed that the primary, secondary and high frequency response are paid in an average price of 8 £/MW/h. In general the regulation prices are lower compared to the Nordic grid where the availability payment also changes every hour.

<table>
<thead>
<tr>
<th>EFA Block</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23:30 - 03:00</td>
</tr>
<tr>
<td>2</td>
<td>03:00 - 07:00</td>
</tr>
<tr>
<td>3</td>
<td>07:00 - 11:00</td>
</tr>
<tr>
<td>4</td>
<td>11:00 - 15:00</td>
</tr>
<tr>
<td>5</td>
<td>15:00 - 19:00</td>
</tr>
<tr>
<td>6</td>
<td>19:00 - 23:00</td>
</tr>
</tbody>
</table>

Table 4: EFA blocks.
2.7 Spot price in Denmark and GB

The cost of energy is calculated with the spot price every hour. Fig.18 shows the spot prices every day of 2018, in both GB and Denmark. For the case in GB the average spot price per MWh is 64.9 €/MWh. A simple tariff model is made by calculating the difference between the average spot price and the average industrial electricity price. In GB the industrial tariff $= 131 - 64.9 = 66.1$ €/MWh. It is assumed that the energy consumption caused by conversion losses for service provision is paid with the industrial electricity price. While the average domestic tariff in GB is, $190 - 64.9 = 125.1$ €/MWh.[31].

In Denmark the average spot price is 46.19 €/MWh. The average domestic electricity cost including network tariffs and taxes is relatively high at 307 €/MWh, while the average industrial electricity cost is only 80 €/MWh. The industrial tariff is $\text{tariff}_{\text{industrial}} = 80 - 46.19 = 33.81$ €/MWh while the domestic tariff is $\text{tariff}_{\text{domestic}} = 307 - 46.19 = 260.8$ €/MWh.[32].

Figure 18: (a) Spot market prices every day of 2018 in GB. (b) Spot market prices every day of 2018 in Denmark.

Concluding, it is worth mentioning that the average spot price in Denmark is lower than GB’s. The reason might lie in the fact that the grid in Denmark is better interconnected compared to GB.
3 Analysis of driving behavior

3.1 Evolution of the European electric car stock

Electric vehicles include both Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs). The share of BEVs in the overall electric car stock continued to grow at moderate rates. There was a growth of 0.72 million Evs in Europe between the 2013-2017 period. While Norway has the highest per capita ownership in EVs.

![Number of electric vehicles in Europe](image)

Figure 19: Number of electric vehicles in Europe

Fig. 20 shows the stock of electric cars in the Nordic region increased since 2010. With 176,000 electric cars in 2017, Norway accounts for 70% of the stock of electric cars in the Nordic region. Sweden has more than 49,000 electric cars in circulation and accounts for 20% of the total Nordic stock. Despite a decline in sales in 2016 and 2017, Denmark has the third-largest electric car stock in the Nordic region, with 9,900 vehicles. This is roughly double the number in Finland and Iceland, with 6,300 and 5,100 EVs respectively.

![The electric car stock in Nordic Region since 2010](image)

Figure 20: The electric car stock in Nordic Region since 2010

Current market size, announced policies and climate ambitions in the five Nordic countries suggest that the EV stock is could reach 4 million units by 2030. As it can be seen more clearly in Fig. 21, Norway has the leading role among the five Nordic countries. Although, global sales
increased 54% in 2017, helping EVs remain on track to reach the Sustainable Development Scenario target, one of its main goals is to tackle the climate change, there’s still a long way to go.

![Figure 21: Deployment scenario of electric vehicles in Nordic region][34]

### 3.2 Driving data overview

EVs can, when they are not used for driving, create value for the EV owner, by delivering ancillary services to the transmission system operator. When calculating the potential earnings from grid services and charging strategies it highly depends on the driving time, driving distance and time spent at different locations.

The telematics data from U.S. with the drive and charge events, is comparable to European driving behaviour and is then used in a simulation based on the Danish grid code and measurements of the Danish system frequency but also the GB system frequency and grid code. The data set, is collected from EVs where the owner has accepted to share data at the time of purchase, and corresponds to 50% of the sold EVs of the specific model. It should be mentioned that the specific EV, Nissan LEAF, is the most sold EV worldwide[35]. The data is anonymized but shows the daily behaviour of each EV during 2015. A time vector is generated for each EV with a value every 15 minute interval during the year. Each value specifies if the EV is being driven, charging or if it is parked at one of the following locations:

- Household
- Work place
- Other location
- Unknown location

The driving distance of each trip is expressed in km, while the charging pattern, consists of power measurements expressed in kWh for the time periods that the EV is parked throughout the day. The three above-mentioned locations are pretty accurate and were obtained based on the Global Position System (GPS) of each EV. Knowing when the EV is in motion, charging or parked a different set of useful patterns can be derived.
3.3 Analysis of U.S. EV driving data

The scope of this chapter is analyzing the users driving behaviour, using the driving data from Nissan, to understand when the vehicles are utilized during the day. The period of time when the vehicles are not driven, they can be charged or used for supplying ancillary services to the grid. Since the available time is usually longer than the time needed to charge the battery, the vehicles could be used to provide services, offering reliability to the power system, while at the same time originating economic incentive for the EV owner[36]. Therefore, it is essential to understand the pattern of the available hours and see if there are ways to predict them.

Taking into consideration the daily routine of an average person, there are two main time periods, that can be defined. The work time period and the home time period. During the work time period the vehicles, are either driven or parked. In case the vehicles are parked during this period, there is a chance for the owners to charge them, using public chargers. However, it is believed that most of the charging is done when the vehicle is located at home[37], which is also an observation based on the following driving data. Subsequently, the revenues acquired, when the vehicles are charging during the working hours are not taken into consideration.

3.3.1 Driving behavior in U.S. and Denmark

The driving behaviour in the U.S. is compared with the driving behavior in Denmark to show that the findings are similar. The national Danish Travel Survey is based on conventional (ICE) vehicles in Denmark but it is found that the driving behaviour is identical.

Fig[22] shows the distribution of the accumulated driving distance for each EV in one year, in U.S.. The average driving distance is 17.2 k km/year equal 47 km/day which is higher compared to Denmark, where the average driving distance is 44.1 km/day for weekdays and the overall driving distance of passenger cars is 45 km/day[38].

![Figure 22: Distribution of the yearly driving distance](image)

Fig[23] is a representation of the distance driven in a day, in U.S. The average value is close to the average number of km driven in Denmark.
Fig. 23 shows, the average driving time is 228 hours/year in U.S, giving an average utilization of 2.6%. While the situation in Denmark is similar [31].

Even though landscape, weather, culture, between Denmark and U.S are different, the two countries have a similar average driving behavior. With an average driving distance 40.1 km/day and a medium-sized EV’s travel range of approximately 170 km, it is clear that the EV can adequately satisfy the average driving need [30]. Despite the differences between the countries, my aim is to describe the EV driving and charging patterns. The analysis is based on US driving data from Nissan, but due to the similarities with Denmark, the basic idea would be the same. However, it is worth mentioning that since the data come from a Nissan LEAF with 24 kWh it is not representative of all the ICE passenger cars in Denmark.
3.3.2 Driving and charging pattern analysis

For the purpose of analyzing the driving and charging schedule of EVs in Denmark, the driving pattern of EVs in U.S will be studied. As already mentioned, in the previous subsection, there are many similarities between the driving behavior of the vehicle owners in the two countries. Therefore, it is reasonable to use the telematics data from the U.S area for the analysis. The analyzed driving and charging profiles for 7163 EVs are presented thoroughly and finally a comprehensive summary is given.

The analysis of the driving time and distance, is based on the beginning and ending of each trip. The driving distance of each EV is used to calculate the energy requirements of each vehicle. The driving destination of each trip, can determine the availability of each vehicle. If an EV is being driven, it is not possible to charge at the same time. In order for an EV to charge or discharge, there should be an exchange of energy between the vehicle and the grid, otherwise the vehicle can be parked at the driving destination.

Fig. 25 shows the share of the EVs driving and charging behaviour, during weekdays. From the following graph it is confirmed that the driving and charging pattern are similar for weekdays throughout the year. The blue line of the graph depicts the share of the EVs that are driving during the day and the red line shows the share of the EVs that are charging at the same time. It can be seen that despite the data is from EVs with 24 kWh battery capacity, the charging peak is considerably low for all the EVs charging concurrently and that is a sign that the owners do not charge their vehicle every day, as long as they don’t have to drive a very long distance the next day 28.

On weekdays, the share of EVs driving, rises in the morning when people are supposed to leave home for work, at 7:00 - 8:00 with EV driving behavior reaching a peak of about 10%. In the evening, there is another peak of the EV driving share, around 17:00 to 18:00 when people are supposed to leave working places for home. After that, the share of EVs driving, decreases constantly until midnight, which is nearly 0%. A similar case of driving and charging behavior, applies in Denmark 40.
Figure 25: Share of EVs driving and charging, during 18th - 22nd of January 2015 (Monday-Friday).

It is important to mention that although the driving and charging pattern is identical for every week day, there is one day that the driving activity is lower during 07:00 - 10:00 and 17:00 - 20:00. This specific day is Friday and the driving behavior can be justified by the fact that a reduced number of EV owners drove at their work that day.

Fig 26 is shown the driving and charging behavior during the weekend. It can be observed that the EV driving pattern is different on the weekend compared to a work day. The share of EVs that are driving on weekends is noticeably lower, without any remarkable peaks. There is a gradual increase of the share of EVs driving, around 7:00 - 8:00 which reaches a peak with about 5%, around 12:00 at the noon. Then there is a progressive decrease until midnight when the share of EVs driving is close to 0%.
The different percentiles for driving and charging during the whole year, are presented below. Fig. 27 shows the percentile bands when the EVs are driving during week days and weekends. According to the scale of y axis the driving activity of the EVs lies within a certain range of values. For example, if a value is at the 80th percentile, where 80 is the percentile rank, it is equal to the value below which 80% of the observations may be found. However, if it is within the 80th percentile, which means the score is at or below the value below which 80% of the observations may be found.

It should be mentioned that 1st of January and 4th of July were considered weekends since they are major holidays. Thus the driving and charging activity on these days, differ significantly compared to the rest of the week days.

Figure 27: (a) Percentiles bands for driving activity during week days. (b) Percentile bands for driving activity during weekends.
The percentile bands show a similar pattern with Fig. 26, however they contain an uncertainty of a value to be within a certain range.

Fig. 28 is a similar representation of the percentile bands, but the way those bands are calculated is different. Unlike Fig. 27, where the bands were calculated based on the formula of the confidence interval (Eq. 14), these plots are calculated based on the max and min values of the actual measurements. The results are similar, however, the theoretical approach contains a bigger uncertainty, as a result the percentile bands are appeared more spread, than the real ones.

Figure 28: (a) Percentiles bands for driving activity during week days (measured). (b) Percentile bands for driving activity during weekends (measured).

Fig. 29 shows the percentile bands when the EVs are charging during week days and weekends, according to the data set that contains the actual values of charging. The vertical axis shows with a certain probability the charging activity during the day.

Figure 29: (a) Percentiles bands for charging during week days. (b) Percentile bands for charging during weekends.
Once again, the theoretical way of calculating the percentile bands (Fig.29) is compared with the actual way, in Fig.30. The results appear to be similar but with a lower spread.

Figure 30: (a) Percentiles bands for charging during week days (measured). (b) Percentile bands for charging during weekends (measured).

3.3.3 Availability analysis

The share of EVs that are parked is illustrated, in the following Fig.31. This share represents the time when the EVs are available for charging. The availability drops to around 93% around 7:00 - 8:00 and then rises up again in the middle of the day. At that point it declines steadily until the afternoon around 17:00 - 18:00, where it starts rising up again until midnight. The availability curve is more gentle on weekends, when the EV owners have no obligation to go to work, but also the overall availability is obviously higher than that of weekdays in general. For a share of personal vehicles greater than 96%, parked the most of the time, this is a huge potential for the EVs for utilizing the battery capacity during this time. The EVs are however only available for the grid when they are plugged in, which does not happen every day and especially during working hours.
In Fig. 31 is depicted the share of personal EVs that are parked during a weekend. This pattern is representative for every weekend during 2015. As it was expected the most of the vehicles are parked during morning and night hours, the same hours while the EVs are charging. During the day, more specifically during 09:00 - 19:00 the vehicles are in motion.

In the present thesis, the EV is used for grid services that generate revenues for the EV owners when they are not used for driving and it is therefore assumed that it is plugged in when it arrives at the household.
The distribution of the availability of EVs, during a day when the vehicles are parked at home, work or some other location is illustrated in Fig. 33. Additionally, for a more accurate approach the distribution of missing data is plotted and is labeled as "Unknown". During this period the EV is either parked at home or work or driving, but since they are not clear their value is set to zero. The percentage of missing data is only 1.36%.

The EV availability when the vehicle is parked at "Home" follows a different distribution compared to the availability at "Work" or some "Other" location. The availability for EVs at "Home" drops below 50% in the middle of the day and rises up steadily from the afternoon until the night, while the availability for vehicles at "Work" rises during the day and steadily declines during night. This makes sense since the vehicles are mostly parked at the working place during day-time. It is also worth mentioning that although the availability of vehicles at "Home" is around 75% during morning and night hours, only a small percentage is charging as it is shown in Fig. 33.

![Figure 33: (a) Distribution of EVs at home and work, during 5th of January 2015 (Tuesday) (b) Distribution of EVs at home, work including other location and missing data during 6th of January 2015 (Wednesday).](image)

As shown in Fig. 33 the EV availability when the vehicle is at "Home" follows a different pattern compared to when it is parked at "Work" or some other location. A similar trend applies also for a representative day during the weekend. However, the EV availability curves are more gentle, with a portion of vehicles moved from location "2" and "3" to location "1". The results are reasonable since not so many people are working during weekends. Furthermore, the overall availability of weekends is obviously higher than that of weekdays in general, which is similar in Denmark.
The EV charging analysis is based on the driving analysis of the U.S region, described earlier in section 3.3.2. In the EV charging analysis, each vehicle is charged according to its own driving pattern, depending if it is at home or work. The accumulated electrical charging curve for a total number of 7163 vehicles is generated. It is not the mean obtained from the total number of EVs but the aggregated charging power for a whole year, presented in a time axis of 24 hours.
In the following figures the accumulated charging power for two different days is demonstrated. As it was expected the accumulated charging power pattern in both Fig.35 and Fig.36 is similar with the charging pattern in Fig.25 and Fig.26, respectively.

On week days, during morning and night hours the accumulated charging capacity is on its climax. However, during the day the power drops significantly, which makes sense since the most of the EVs are located at work, thus it is not possible for all of them to be charged.

On weekends, the most of the charging is done during morning hours, after that there is a steep fall in the accumulated charging capacity since the most of the EVs are either driven or parked in some other location.

Figure 35: Accumulated charging power every 15 min. for 7163 EVs on 7th of January 2015 (week day).

Figure 36: Accumulated charging power every 15 min. for 7163 EVs on 17th of January 2015 (weekend).

These two days, were chosen as representative examples since the pattern is the similar for all the week days and weekends during the year.
4 Analysis of system’s frequency

4.1 Frequency behavior throughout the year

A frequency analysis is performed for the Danish system. The data set consists of yearly frequency measurements for 2016. The sample rate of the investigated period is 10 seconds and the resolution of each sample is $1 \cdot 10^{-3}$ Hz. Frequency deviations, result in an energy exchange between the BRP and TSO, if the average value of frequency is 50 Hz, the energy exchange is expected to be zero, excluding the energy losses.

Fig. 37 shows the frequency measurements for 2016 in Denmark. Having an average frequency variation around 50 Hz, results in a zero energy exchange or in other words there is no energy bias. The different colors of the figure, indicate the frequency measurements for each month separately during 2016.

![Danish Grid Frequency in 2016](image)

Figure 37: Danish frequency profile for 2016.

Fig. 38 shows a histogram of all the frequency samples for 2016 in Denmark. The fit follows a Gaussian distribution with an average value of 50 Hz, throughout the year.
4.1.1 Energy content model

The energy exchange with the grid, is calculated as the offset of the positive and negative values, corresponding to the frequency deviations. Even though the energy bias can be zero in the long term, it can become very intense in shorter periods.

Assuming a constant power $P_{cap} = 10$ kW for FCR-N provision, the following Fig.39 shows the accumulated $E_t$, during 48 hours in January. As it can be seen, even though the $E_t$ fluctuates around zero, it also changes substantially during the day, which is the time horizon for bid and settling of the FCR-N procurement.

In case of a FCR-N provision with EV, in order to ensure that all the short-term unbalances are settled, the capacity of the battery should be large enough, to accommodate the demand for energy.
The accumulated energy, up to time step \( t \), since the beginning of the FCR-N provision, assuming that there are no conversion losses, is calculated with the use of the following formula:

\[
E_t = E_{t-1} + P_t \cdot t
\]  

(12)

The accumulated energy content can be calculated by integrating the frequency deviations during a certain period. In this case, it is calculated for every 15-minute period of the year so it has the same time resolution as the driving consumption data. The integration of frequency deviations of a given 15-minute period \( n \), also known as the energy content of that period, is denoted by \( E_{bias}^h \). In Denmark, for a sample rate of \( t_s = 10 \text{ s} \), the number of samples per 15-minutes period is equal to \( N_p = 90 \).

The sum is divided with the number of samples per hour, \( N_h = 360 \) for a unit in kWh. The per unit (p.u.) energy content, that is normalized per kW of regulation capacity, is given by:

\[
E_{bias}^h = \frac{1}{N_h} \sum_{t=N_p(h-1)+1}^{h \cdot N_p} y_t \cdot t_s
\]  

(13)

Even though the energy balance can change significantly in the long term, the FCR-N is procured hourly thus it is essential to examine the energy content on an hourly scale. The following Fig.40 shows the energy content for every hour, during January 2016, when the service is provided with \( P_r = 1 \text{ kW} \). 

![Figure 39: Accumulated energy for 48 hours during January 2016](image)
Fig. 40 shows that the energy content of each hour varies between positive and negative values. There are hours where the positive and negative values cancel each other, but there are also hours where the energy exchange adds up.

Assuming still a capacity of $P_r = 1$ kW, the $E_{bias}$ is calculated for 2016 and the results are shown below. Fig. 41 shows the distribution of the energy content in Denmark for a whole year. $E_{bias}$ is Gaussian distributed and is symmetrical around zero. Based on that, the confidence interval can be calculated that it will contain the range of the energy content with a certain probability. It is worth mentioning, that the conversion losses of the power converter are not taken into consideration, in this case.

Fig. 41: Histogram of energy content, every 15 minutes, $E_{bias}$ is fit with a Gaussian distribution $\sim N(\mu = -0.010 \text{ kWh}, \sigma = 0.094)$.

Figure 42
During the FCR-N provision with a storage unit like an EV, the energy that can be stored is limited. For this reason it is essential to make sure that the vehicle will be able to provide FCR-N, at least 99% of the cases. It is essential to guarantee that there is enough energy stored in the battery since FCR-N’s payment is depending on the availability of the EV.

<table>
<thead>
<tr>
<th>Confidence Interval</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>99 %</td>
<td>-0.28</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table 5

Thus, by allocating ±0.28 kWh (see Table 5) in the battery for every kW of FCR-N, the EV would be able to deliver services every 15 min, in 99% of the cases.

The confidence interval is calculated for a power capacity, $P_r = 1$ kW, and increases linearly with the FCR-N capacity. Which means that for $P_r = 10$ kW, it gives a 99% confidence interval of ± 2.8 kWh. The 1% of the cases, are not included since they represent extreme occasions that can rarely occur. However, in order to cover those cases an allocation of ±3 kWh per hour, would be sufficient[41].

Moreover, Fig. 40 shows how $E_{bias}$ varies from positive to negative values during time (t). Therefore, this exchange of energy results in a lower energy balance in the long term. Thus the storage capacity does not have to be (t) times more to make sure that FCR-N can be delivered.
4.2 Investigation of the energy content

4.2.1 Energy Content of Denmark’s system frequency

Fig. 43 shows the cumulative energy balance in Denmark, since the beginning of service provision for a duration of 24 hours for 30 days. Assuming a 24-hour service period with $P_r = 10 \text{ kW}$. The energy balance is a result of the accumulated power required by the service provider, over time (see Eq.9), and the calculation is made without taking the conversion losses of the power converter into consideration. For a statistical evaluation of the results a higher number of samples is required.

Figure 43: Energy balance in January 2016 in Denmark, when delivering frequency regulation with $P_r = 10 \text{ kW}$, excluding the efficiency and for a frequency deviation $\pm 0.1 \text{ Hz}$.

In Fig. 44 the energy balance, is depicted for a whole year. The graph is made that way in order to make visible the numerous number of simulations that are plotted. It is very clear that the variance of the energy balance increases along with the limits of the confidence interval.
Figure 44: Energy balance in 2016 in Denmark, when delivering frequency regulation with \( P_r = 10 \text{ kW} \), excluding conversion losses for a frequency deviation \( \pm 0.1 \text{ Hz} \).

The formula for the calculation of the confidence interval is:

\[
\text{Conf.int} = \bar{x} = z \cdot \frac{\sigma}{\sqrt{n}}
\]  

(14)

Where \( \sigma \) = standard deviation, \( n \) = sample size, \( z \) = confidence coefficient and \( \bar{x} \) = sample mean. Note that \( z = 2.58 \) value is taken from the standard normal (Z-) distribution. The confidence interval is a range of values that gives with a certain precision the estimation of the energy balance. In this case, the 99\text{th} degree confidence interval is used.

<table>
<thead>
<tr>
<th>Confidence interval (99%)</th>
<th>Minimum (kWh)</th>
<th>Maximum (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>-40.87</td>
<td>36.47</td>
</tr>
</tbody>
</table>

Table 6

The energy balance is less symmetrical around 0, however in 2016 the energy content is slightly negatively biased, which means that by the end of the investigated period the energy that consumed from the grid is less compared to the energy injected to the grid. Moreover, the increased number of samples gives a better statistical evaluation with the use of confidence interval. It is also worth mentioning that the energy converges due to the cancelling out of the energy exchange every hour.
4.2.2 Differences between Denmark and GB

The energy content of the GB frequency is slightly higher compared to the Nordic grid. The main reason is the small size of the GB system and the large amount of renewable energy that is produced. Because the full response is given for a deviation of ±0.2 Hz and not ±0.1 Hz, which is the case in the Nordic grid, the variance of the energy content experienced by the service provider, is a bit lower compared to Denmark.

An interesting observation is made on the following Fig 45. A simulation of the energy balance both in Denmark and GB was plotted, with the same scaling limits. This time the same frequency deviation was used (±0.1 Hz). The intention was to make clear that the energy content in GB is more intense compared to the Nordic grid. The reason is the high penetration of renewable energy sources in GB, which lowers the system inertia. Thus the energy content in the end tends to be higher.

Figure 45: (a) Energy balance in 2017 in GB, when delivering frequency regulation with \( P_r = 10 \text{ kW} \), including conversion losses for a frequency deviation ±0.1 Hz. (b) Energy balance in 2016 in Denmark, when delivering frequency regulation with \( P_r = 10 \text{ kW} \), including conversion losses for a frequency deviation ±0.1 Hz.
4.2.3 Without conversion losses

In Fig. 46 the cumulative energy balance is shown, both in GB and Denmark, assuming a 24-hour service period with \( P_r = 10 \text{ kW} \), without taking the conversion losses into consideration.

![Figure 46](image)

Figure 46: (a) Energy balance in 2017 in GB, when delivering frequency regulation with \( P_r = 10 \text{ kW} \), excluding conversion losses for a frequency deviation \( \pm 0.2 \text{ Hz} \). (b) Energy balance in 2016 in Denmark, when delivering frequency regulation with \( P_r = 10 \text{ kW} \), excluding conversion losses for a frequency deviation \( \pm 0.1 \text{ Hz} \).

<table>
<thead>
<tr>
<th>Confidence interval (99%)</th>
<th>Minimum (kWh)</th>
<th>Maximum (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB</td>
<td>-26.47</td>
<td>26.09</td>
</tr>
<tr>
<td>Denmark</td>
<td>-40.87</td>
<td>36.47</td>
</tr>
</tbody>
</table>

Table 7

In GB the energy balance is symmetrical, however in Denmark the energy balance is more shifted to the negative side. The fact that the response service in Denmark is activated for smaller frequency deviations plays a significant role on this matter.

4.2.4 The effect of the conversion losses

In Fig. 47 the cumulative energy balance is shown, both in GB and Denmark, assuming a 24-hour service period with \( P_r = 10 \text{ kW} \). But this time, the conversion losses are taken into consideration. A constant efficiency \( \eta = 0.9 \) is assumed, which is a realistic scenario [41]. The efficiency applies in both directions, meaning from the grid to the battery \( P_{AC}/P_{DC} \) and from the battery to the grid, \( P_{DC}/P_{AC} \), thus \( \eta_c = \eta_d \), respectively. By adding the conversion losses the energy balance moves towards the negative side, for the case in GB. In Denmark the energy balance becomes even more negatively biased, while the variance still remains. The high variance with a biased energy balance, has a crucial effect on the potential profit of the BRP since it affects the energy exchange, between BRP and TSO. For an EV that procures frequency regulation for many hours consecutively the high variance might cause violation of constraints.
the SOC constraint limits. To deal with the high variance, an allocation of power for correction is essential and it will be discussed more in detail, in the following chapters.

![Figure 47](image)

**Figure 47:** (a) Energy balance in 2017 in GB, when delivering frequency regulation with $Pr = 10\ kW$, including conversion losses for a frequency deviation $\pm 0.2\ Hz$. (b) Energy balance in 2016 in Denmark, when delivering frequency regulation with $Pr = 10\ kW$, including conversion losses for a frequency deviation $\pm 0.1\ Hz$.

<table>
<thead>
<tr>
<th></th>
<th>Confidence interval (99%)</th>
<th>Minimum (kWh)</th>
<th>Maximum (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB</td>
<td>-32.52</td>
<td>20.14</td>
<td></td>
</tr>
<tr>
<td>Denmark</td>
<td>-49.51</td>
<td>27.37</td>
<td></td>
</tr>
</tbody>
</table>

*Table 8*

The range of the confidence interval is larger to some extent compared to the cases where no losses are taken into account (see Fig. 46). In both cases, the energy balance is negatively biased, which means, at the end of the investigated period the energy supplied to the grid is higher compared to the energy consumed from the grid, for service provision as an effect of the efficiency losses.

The high variance in the Danish grid creates higher deviations of the energy balance from the mean. Also the different response mechanisms for frequency regulation between GB and Denmark, combined with the existence of conversion losses, shift the danish energy balance more to the negative side compared to GB.

The expected energy exchange between grid and EV battery increases (in absolute values).

The following Fig. 48 shows the average amount of energy losses per EV per year for both Denmark’s and GB’s energy content. Considering a charger’s nominal capacity of $\pm 10\ kW$, the effect of the efficiency, $\eta = 0.9$, on the service provision, leads in the following results.
Figure 48: (a) Distribution of yearly energy losses in GB for 7163 EVs. (b) Distribution of yearly energy losses in Denmark for 7163 EVs.

In the following Table 9, the results of the average amount of energy losses per EV per year, for both Denmark and GB, are summarised.

<table>
<thead>
<tr>
<th>Energy losses (kWh)</th>
<th>GB</th>
<th>Denmark</th>
<th>per year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>687</td>
<td>1147</td>
<td></td>
</tr>
</tbody>
</table>

Table 9

The average amount of losses is based on the measurements for frequency regulation from a sample of 7163 EVs. The large margin in energy losses between Denmark and GB is due to the difference in availability hours for the EVs, to provide frequency regulation. This amount of losses in the end of the service provision, results in a lower SOC level for the EV battery. In general, the effect of losses weighs heavily upon the EV owner since the amount of energy that has to be transferred from the DC side to cover the energy losses is higher. At the same time the EV battery will receive less power compared to what is drawn from the AC side. The hourly energy losses from the FCR-N service, will be paid with the danish electricity price of that hour, including the additional tariffs.
5 Electric vehicle charging and service provision

5.1 Formulation of charging behavior

The formulation of charging behavior, based on the driving trips and the corresponding driving consumption, of the individual EV profiles is described in detail. It should be mentioned, that the base code in Python that the following model is built upon, was provided by Nissan.

The support of the power grid with the deployment of EVs, might raise some concerns. Thus a good plan is to meet the challenge of EVs as an additional type of load in the system. Uncontrolled charging from a large fleet of EVs has a risk to cause unnecessary congestion to the distribution. Considering the case of bidirectional chargers, the availability of EVs is a crucial factor to determine whether or not they are capable to provide primary frequency regulation to the grid. Moreover, low state of charge by the end of the service provision, can be a problem for the EV owners when it comes to consumption for their next trip. Subsequently, the SOC constrains should be respected, which is also a crucial element when it comes to degradation of the battery.

Modelling the EV charging behavior is essential to assess the impact not only on the distribution grid but also on the EV owners. However, in order to build a robust model, the use of a large sample of accurate driving data is essential, like the ones that was acquired by Nissan. The data includes the daily travel distance per vehicle, as well as the arrival time at household or work. When the vehicle is located at home or at work, it is available for charging but it is available to provide ancillary services to the grid only when it is located at home. However, the EVs are charged depending on their needs, which are related with the driving distance of the following trip. Only EVs used for long distance driving are plugged with higher frequency, in contrast with the majority of the EVs that are charged only a few times per week when the SOC is low or not within the suggested limits.

Moreover, an initial SOC of 50% is considered and the recommended operated limits for a Nissan LEAF (which is the vehicle from which the driving data is taken from) are within 20% - 90%, to avoid excess wear of the battery. It is necessary to charge the EV to a certain level before the next departure since this could influence the time for FCR-N. The EV is always to be charged dynamically based on the initial 50% and the expected driving consumption.

The flexibility of the EV depends on the plugged in time, the daily energy consumption for driving, the energy content of the frequency the energy capacity of the battery and the charging power.

The current analysis considers DK2 area as a case study. However, with some modifications regarding the power allocated for regulation and correction along with the allocation of time for frequency regulation, it can be also simulated for GB’s power market. Another essential aspect is the battery degradation as a result of the extended use of the battery. Degradation comes from both cycle degradation as a function of the number of equivalent full cycles and calendar aging as a function of time passing at different SOC and temperature.
This model is built considering EV usage for several strategies. EVs start to charge or provide frequency regulation as soon as they are available to connect to the grid. EVs should be adequately charged, before the departure time for the next trip and afterwards. Whereas, charging and discharging individual profiles should be controlled in order to fulfill the economic objectives and SOC constrains and operate in the most profitable way for the EV owners.

Based on the driving behavior of the EV owners that was analyzed in section 3.3, the departure time, the arrival time on the destination as long as the daily driving distance are known for 7163 EVs. The time step \( (t_i) \) is every 15 minutes for a whole year. However, the spot markets prices, that are used for the revenue calculation, are constant within an hour. Furthermore, the EV battery characteristics are equal for all profiles. The nominal capacity of the battery is considered 40 kWh, like the one for a NISSLAN LEAF 2018 model, while the charging/discharging maximum power rate is 10 kW with an average efficiency of \( \eta = 0.9 \) and an energy consumption for driving equal to 5 km/kWh per vehicle (see section 1.3.1).

It is assumed for simplicity that EVs are available for charging when they arrive at household for this reason workplace or any other places with public chargers are not taken into consideration. However, not every EV is plugged in when it arrives at the household. The percentage of plugged in EVs depends on the SOC of the battery and the daily driving distance. For example, a vehicle is charged if the SOC of the battery is low and/or has a long trip the following day. On the other hand, if the SOC is high and/or the daily driving distance is short there is no need for charging.

A data set that contains information about the driving behavior of all the users is obtained, thus there is no need to make any predictions since the outcome is determined based on known relationships. Theoretically, the users can essentially plug-in their vehicle as soon as it is located at home. The data set contains information for 7163 EV users but for the sake of simplicity, a detailed description for three of them will be made.

A sample of three different driving profiles, has been defined from the full data set, summarized in the following Table 10.
"Time" represents the periods, each of them is 15 minutes, thus in total a 3 hour period is shown. The missing values are marked as "zeros" while the availability when the vehicle is parked at the household or at work, is indicated as "1" or "2" respectively. During these periods the EVs could participate in the energy market or they could charge. For values, $x_{t_i,j} > 100$, the vehicle is driving.

The driving distance of each trip is calculated as follows.

$$driving_{trip} = (x_{t_i,j} - 100) \ km$$

Where $t_i$ denotes the specific time period and $j$ indicates the corresponding EV user. Each time period is equal to 15 minutes.

Thus the period from $t_1$ to $t_4$, for $EV_0$, signifies a driving trip that lasted one hour.

The value: 108, signifies the driving distance of this trip, which according to Eq.15 is 8 km. The fact that the value is repeated, indicates the duration of the same trip, meaning 1 hour since $t_i = 15 \ min$.

The exact time when the EV starts driving is calculated for every individual profile. A function is made that finds the first 15 minutes when the trip starts, denoted as trip starting time, along with the corresponding EV profile. The function iterates through the driving data and finds all the values greater or equal to 101 ($driving \geq 101$). Afterwards, it creates a frame. The first column of this frame, takes as input the exact quarter before the trip starts as well as the profile of the corresponding EV, see table 11. Since the data set contains information for a whole year, the corresponding number of time values should be, $0 \leq t_i \leq 35.040$, $(24 \cdot 4 \cdot 365 = 35.040)$ and for the EV profile, $0 \leq EV_j \leq 7163$. 

<table>
<thead>
<tr>
<th>Time</th>
<th>EV$_0$</th>
<th>EV$_1$</th>
<th>EV$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_0$</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$t_1$</td>
<td>108</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$t_2$</td>
<td>108</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$t_3$</td>
<td>108</td>
<td>113</td>
<td>1</td>
</tr>
<tr>
<td>$t_4$</td>
<td>108</td>
<td>113</td>
<td>1</td>
</tr>
<tr>
<td>$t_5$</td>
<td>1</td>
<td>1</td>
<td>110</td>
</tr>
<tr>
<td>$t_6$</td>
<td>1</td>
<td>1</td>
<td>110</td>
</tr>
<tr>
<td>$t_7$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$t_8$</td>
<td>116</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$t_9$</td>
<td>116</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$t_{10}$</td>
<td>102</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$t_{11}$</td>
<td>102</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 10
Sometimes a second trip follows the first one and the need to differentiate the trips between each other is essential for the calculation of the driving consumption. Thus the second part of the function includes a formula that calculates whether there is a second trip or not. This is executed by comparing the values within the quarters of the driving trips and if the values are differ from each other, \( \text{driving}_{\text{trip}(t_{i-1})} \neq \text{driving}_{\text{trip}(t_i)} \), then a follow up trip takes place. A frame that includes the times of the consecutive trips and the respected EV is created, see Table 12.

<table>
<thead>
<tr>
<th>Number of trips</th>
<th>Second trip</th>
<th>EV No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>( t_{10} )</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 12

Based on Table 10, only EV_0, has a second follow-up trip, that took place at \( t_8 \).

The energy consumption for each trip is calculated and allocated \( t_{i-1} \), before the trip starts. The period of 15 minutes before the trip starts, for each EV profile, is taken into consideration. For example for EV_0, the trip starts at \( t_1 \), however the energy consumed for driving is allocated in \( t_0 \). The energy consumption for driving (\( E_{\text{drive}} \)) is calculated based on the following equation.

\[
E_{\text{drive}} = \frac{\text{driving}_{\text{trip}}}{5 \text{ kWh km}^{-1}}
\]  

(16)

The \( E_{\text{drive}} \) of each trip, for each individual profile, is shown on the following Table 13.
The negative values indicate the energy needs of each trip.

A function that calculates the energy of the battery for every profile individually, is formulated. The input data is the energy consumed for driving, in each time step \( t_i \), for every EV \( j \). An inner loop updates the SOC of each EV for the examined period, every 15 minutes. In every iteration is calculated the energy of the battery (\( E_{bat}^{t_{i}} \)), which is added to the previous \( E_{bat} \).

If \( E_{bat}^{t_{i}} \geq 0 \), then it is multiplied with the efficiency (\( E_{bat}^{t_{i}} = E_{bat}^{t_{i}} \cdot \eta_c \)) since it is the energy that flows to the battery from the grid, during charging. On the other hand, if \( E_{bat}^{t_{i}} \leq 0 \) it is divided with the efficiency, such as (\( E_{bat}^{t_{i}} = \frac{E_{bat}^{t_{i}}}{\eta_d} \)) since it is the energy that flows from the battery to the grid.

However, the SOC constraints should be respected. For this reason, if during charging time, the SOC \( t_i > 15 \text{ kWh} \), then the charging power is set to 0. On the other hand if the SOC \( t_i < -5 \text{ kWh} \), the charging power, is set to maximum, thus for a time period of 15 minutes the EV should be charged with 2.5 kW, for a bidirectional charger with \( P_{cap} = 10 \text{ kW} \). These constraints should be respected in order to maintain the SOC of the battery within the desirable limits [20% - 90%]. Additionally, an initial SOC is set in the beginning of the period, at 50% of the nominal capacity of the battery, meaning 20 kWh.

The purpose of setting these constrains is to keep the SOC of the battery within [8 - 36] kWh.

The energy needs for each trip and the time period where the EV is charging are formulated. During this period the vehicle is not available to provide FCR-N. The charging time (\( Ch_{time} \)), which is the duration of the charging period, has to be calculated first, based on the \( E_{drive} \) that is already known, from Table 13.

Taking into account the \( P_{cap} = 10 \text{ kW} \), the number of time slots needed for charging before the trip are determined. If the charging losses were neglected, with a 10 kW charger an amount of \( E_{drive} = 10 \text{ kWh} \) could be provided in one hour. However, since the time step is 15 minutes, 2.5 kW of the \( P_{cap} \) should be allocated in each \( t_i \).

In this model the conversion losses are taken into consideration. So, for a \( E_{drive} = 1.6 \text{ kWh} \) an additional charging losses equal to 0.16 kWh will be added,
considering $\eta_c = 0.9$. Meaning that the total energy for charging ($E_{Ch,tot}$) is 1.76 kWh.

The time when the trip starts is already known but the allocated Ch$_{time}$, needs to be determined. The Ch$_{time}$, is calculated after rounded up the result of Eq.(17) since the time frame should be an integer value.

$$Ch_{time} = \frac{E_{Ch,tot}}{2.5 \cdot \eta_c}$$

On the numerator, the $E_{Ch,tot}$ signifies the $E_{drive}$ including the losses. On the denominator the max limit for charging in kW per $t_i$ is multiplied with the $\eta_c$.

The $E_{Ch,tot}$ for each trip is divided equally, and distributed in each time slot, $t_i$, of the charging window, based on the Ch$_{time}$. In this example, the Ch$_{time}$ is distributed in one time slot, thus it will last 15 min.

For $E_{Ch,tot} = 1.76$ kWh, the $E_{Ch,ti}$ per $t_i$, is:

$$E_{Ch,ti} = \frac{E_{Ch,tot}}{Ch_{time}} = 1.76 \text{ kWh}$$

The results are finalized on Table 14.

<table>
<thead>
<tr>
<th>$t_i$</th>
<th>EV$_0$</th>
<th>EV$_1$</th>
<th>EV$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_0$</td>
<td>1.76</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$t_1$</td>
<td>-1.6</td>
<td>1.43</td>
<td>1</td>
</tr>
<tr>
<td>$t_2$</td>
<td>108</td>
<td>1.43</td>
<td>1</td>
</tr>
<tr>
<td>$t_3$</td>
<td>108</td>
<td>-2.6</td>
<td>1</td>
</tr>
<tr>
<td>$t_4$</td>
<td>108</td>
<td>113</td>
<td>2.2</td>
</tr>
<tr>
<td>$t_5$</td>
<td>1</td>
<td>1</td>
<td>-2</td>
</tr>
<tr>
<td>$t_6$</td>
<td>1.98</td>
<td>1</td>
<td>110</td>
</tr>
<tr>
<td>$t_7$</td>
<td>1.98</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$t_8$</td>
<td>-3.96</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$t_9$</td>
<td>116</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$t_{10}$</td>
<td>102</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$t_{11}$</td>
<td>102</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 14

The same procedure is formulated for all the 7163 EVs during a period of one year. The data frame is updated with the driving and charging behavior of each EV. The reason is that the time period when the EV is driving or charging and thus is unavailable to provide ancillary services, has to be defined.

It can be stated that the individual EV profiles charging every day are different, however the
charging pattern is similar for weekdays and week ends, as it is shown in \[3.3\].

After that, the Table [15] is updated, in order to distinguish the time periods while the EV is charging and thus it is not available to provide frequency regulation services. For this reason the values of the time slots while the EV is charging are replaced with a value = 10.

<table>
<thead>
<tr>
<th></th>
<th>EV(_0)</th>
<th>EV(_1)</th>
<th>EV(_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t_0)</td>
<td>10</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>(t_1)</td>
<td>-1.6</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>(t_2)</td>
<td>108</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>(t_3)</td>
<td>108</td>
<td>-2.6</td>
<td>1</td>
</tr>
<tr>
<td>(t_4)</td>
<td>108</td>
<td>113</td>
<td>10</td>
</tr>
<tr>
<td>(t_5)</td>
<td>1</td>
<td>1</td>
<td>-2</td>
</tr>
<tr>
<td>(t_6)</td>
<td>10</td>
<td>1</td>
<td>110</td>
</tr>
<tr>
<td>(t_7)</td>
<td>10</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(t_8)</td>
<td>-3.96</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(t_9)</td>
<td>116</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(t_{10})</td>
<td>102</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(t_{11})</td>
<td>102</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 15

5.2 Allocation time for frequency regulation

The period when the EVs are available to provide frequency regulation has to be determined and the Table [15] that includes all the information about driving trips and charging for each EV, has to be updated. When the vehicles are neither charging or driving and they are at home, they are available to provide frequency regulation.

The values of the time slots where the EV is available to provide frequency regulation, are replaced with a value = 11.

<table>
<thead>
<tr>
<th></th>
<th>EV(_0)</th>
<th>EV(_1)</th>
<th>EV(_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t_0)</td>
<td>10</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>(t_1)</td>
<td>-1.6</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>(t_2)</td>
<td>108</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>(t_3)</td>
<td>108</td>
<td>-2.6</td>
<td>1</td>
</tr>
<tr>
<td>(t_4)</td>
<td>108</td>
<td>113</td>
<td>10</td>
</tr>
<tr>
<td>(t_5)</td>
<td>1</td>
<td>1</td>
<td>-2</td>
</tr>
<tr>
<td>(t_6)</td>
<td>10</td>
<td>1</td>
<td>110</td>
</tr>
<tr>
<td>(t_7)</td>
<td>10</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(t_8)</td>
<td>-3.96</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>(t_9)</td>
<td>116</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>(t_{10})</td>
<td>102</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>(t_{11})</td>
<td>102</td>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 16
Table 16 shows that only EV\textsubscript{1} and EV\textsubscript{2} will receive the capacity payment from the reserve market paid in €/kW per hour, for their availability of both EVs during [t\textsubscript{s}-t\textsubscript{11}]. On the other hand EV\textsubscript{0} is not be available and thus it’s not eligible for the payment.

The reserve market dictates that every day the service provision starts at 00:00 a.m. The frequency regulation, has an hourly service window, which means that the individual EV should be available at least one hour, to receive the availability payment.

In this example t\textsubscript{0} is the first hour of the day, meaning 00:00 a.m. According to Table 15, only during [t\textsubscript{s}-t\textsubscript{11}], both EV\textsubscript{1} and EV\textsubscript{2} are available, for a whole hour.

The necessary inputs to formulate the allocation time for FCR-N, are:

- The driving data set that includes the availability of the vehicles when they are located at home, with the time periods when they are driving or charging.
- The P\textsubscript{r} that is allocated for frequency regulation.

Based on these, the time frame when each EV\textsubscript{j} is available for service procurement, as well as the corresponding amount of energy exchange, is calculated.

Apart from the availability service, due to the energy content there are hourly unbalances, that need to be settled.

During the hours that the EVs are available they can also accommodate those unbalances, without violating the SOC constraints. To validate that there are no violations the yearly energy content, \( \sum_{i=1}^{365} E\text{cont}_i \), is taken into account.

### 5.3 Charging cost

The cost of charging (Cost\textsubscript{charge}), for driving purposes, is calculated. The amount of energy used for driving (E\textsubscript{drive}) is subtracted from the total amount of energy used for both charging and driving (E\textsubscript{charge drive}). As a result, the clear amount of energy used only for charging, is multiplied with the electricity price (p\textsubscript{spot}). However, the electricity bill charged from the grid operator, apart from the electricity price per hour, it also includes the domestic tariff which is equal to 0.26 €/MWh. To evaluate the total cost of energy used, (see Table 14) the domestic tariff is also added.

\[
\text{Cost}_{\text{charge}} = \sum_{n=1}^{35039} (E_{\text{charge drive}_n} - E_{\text{drive}_n}) \cdot (p_{\text{spot}_n} + \text{tariff}_{\text{domestic}}) \tag{19}
\]

It should be mentioned that the measurements for E\textsubscript{charge drive\_n} and E\textsubscript{drive\_n} are every 15 minutes. However, the p\textsubscript{spot\_n} changes every hour. Whilst “n”, signifies the 15 minutes time step.
5.4 Energy balance of the battery

The V2G charger has a rated charging/discharging power of $P_{\text{cap}} = \pm 10$ kW, measured at the grid connection on the AC side. When providing FCR-N, a symmetrical response is required, so if the average deviation is zero there will be a zero energy exchange with the grid. In case of an energy exchange with the grid, the service obligation is from the AC side which means that the efficiency losses related to the charger must be covered by discharging the battery of the EV. For this reason, when the EV is charging it receives less power than it is injected from the grid and when it is discharging the power extracted from the battery is higher compared to the power received from the grid.

The following formulas show the calculation of the energy in the battery ($E_{\text{bat}}$) when the EV is charging/discharging. If the EV is charging the energy on the grid ($E_{\text{grid}}$) side will be higher compared to the energy on the battery side and when the EV is discharging the energy on the grid side will be lower compared to the energy on battery side.

$$E_{\text{bat}} = \begin{cases} E_{n}^{\text{grid}} \cdot \eta & \text{if } E_{n}^{\text{grid}} < 0 \\ E_{n}^{\text{grid}} \cdot \frac{1}{\eta} & \text{if } E_{n}^{\text{grid}} > 0 \end{cases}$$

(20)

The $E_{n}^{\text{grid}}$ at period “n”, on the AC side is calculated as:

$$E_{n}^{\text{grid}} = E_{n}^{\text{charge}} + P_{\text{cap}} \cdot E_{n}^{\text{bias}}$$

(21)

In Fig.49 the energy balance of the battery for a period of one year is shown. The SOC ranges between [-3000, +15] kWh, which means that the SOC limits are not respected.

In a real case scenario, the violation of the lower limit would have caused the depletion of the EV’s battery. As a result the EV would not be available to provide FCR-N and the potential revenues from the availability of the vehicle would not be generated.

In this simulation, the lower limit decreases linearly towards infinity, as if the battery has infinite capacity. This linearity towards infinity, is a result of the efficiency losses. It shows that in the long term, a high amount of energy flows from the battery to the grid and is lost as heat is dissipated in the charger, due to the conversion losses.

The red line depicts the 99% of the energy balance in this graph, which derives from the EVs that are less available for service provision during the whole year. On the other hand, the EVs that are available most of the time are the ones that represents the 1% of the energy, which is the reason why the energy in their battery decreases steadily.
5.4.1 Energy balance of the battery, with power correction

As a result of the high energy content allocating 10 kW for frequency regulation, it often leads to energy violations for the SOC of the battery, as it is seen in Fig. 49. For this reason an allocating strategy of 7 kW for power regulation ($P_r$) and 3 kW for power correction ($P_{cor}$), can keep the SOC within the limits of 20% and 90%. The value of $P_{cor} = 3$ kW was chosen, after several simulations, as it is the maximum power for frequency regulation that can be used without violating the SOC limits. As a result the frequency regulation service will no longer be symmetrical [-7, +7] kW in case of a SOC constraint violation. Instead it will be [-5, +9] kW or [-9, +5] kW depending on the SOC, so in the long run the energy balance of the battery will be recovered back within its acceptable limits.

Based on the energy content in Nordic region a regulation capacity of $P_r = 7$ kW is the optimal allocation of power for regulation since it does not result in SOC violations caused by the energy content of the frequency (see section 4.1.1). Respectively a $P_r = 8$ kW is found to be the optimal case for the GB grid, the comparison of these two cases will be shown side by side in section 5.4.3. The $P_{cor}$ is applied when the energy energy exchanged with the grid ($\Delta E$), goes beyond or below the limits during the service provision, since the beginning of the simulation.

\[
E_{cor}^n = \begin{cases} 
    P_{cor} & \text{if } \Delta E_n < -10 \text{ kWh} \\
    -P_{cor} & \text{if } \Delta E_n > 10 \text{ kWh}
\end{cases}
\]  

(22)

As a reminder, the time frame is in quarters of an hour, thus the $P_{cor}$ applied every 15 minutes is also divided in quarters.

The updated $E_{n}^{grid}$ at period “n”, is calculated based on:

\[
E_{n}^{grid} = E_{n}^{charge} + P_r \cdot E_{n}^{bias} + E_{n}^{cor}
\]  

(23)

In Fig. 50 is depicted the energy balance of the battery with the maximum and minimum value out of 7163 EVs, when the EVs are affected by driving consumption, charging and energy content of the frequency with the suggested control strategy. The cumulative sum of the energy of
every profile individually was calculated, in order to present the lowest and highest percentile, 1st and 99th percentile respectively, of the total energy balance. In this particular, graph the energy balance range between $[-10, +15]$ kWh, so for a 40 kWh EV with an initial SOC of 50% it corresponds to a SOC range of $[10 - 35]$ kWh. The control strategy described in the previous section 5.4.1 tries to maintain it within $\pm10$ kWh but if the regulation period is followed by a long trip, it will charge to a higher level to accommodate that consumption. This shows that it is a realistic charging and regulation strategy for an EV with that battery size, however the variance is pretty high. With time allocated for charging and a suitable bidding strategy found, it is possible to calculate a more realistic revenue for a bid of $P_r = 7$ kW.

Figure 50: SOC limits, with efficiency and with allocated correcting power

A similar representation is shown in Fig.51. This time, the initial SOC (50%) is added to make more intuitive the fact that the SOC constraints are respected in all the cases. It is also important to mentioned that every point might be a different EV, since the results were sorted from the lowest to the highest value.

Figure 51: SOC percentage, with efficiency and with allocated correcting power

While Fig.51 plots, the energy in the battery from different EVs every time step, Fig.52 shows the evolution of the energy stored in the battery, of the same individual EV profile, during a 24-hour period. A simulation of 50 cases is chosen since the results are more visible that way.
Once more, the energy profiles are a result of driving consumption, charging and the frequency regulation service, during the examined period. The energy balance of the battery is added to the initial capacity of 20 kWh (50%). There is an efficiency of $\eta = 0.9$ in both directions during the entire simulation, with a $P_r = \pm 7$ kW and allocated $P_{cor} = \pm 3$ kW. Concerning the SOC limits, they are not reached except at a small period around 18:00 p.m when some of the EVs reached their lower limit. The reason that these specific EVs reached their lower limit is a result of a high availability that led to consecutively service provision. However, the period is short, meaning that the EVs are almost always available to provide FCR-N.

![Figure 52: SOC schedule during 24 hours (January 2nd), with efficiency and with allocated correcting power](image)

### 5.4.2 Energy balance with neither efficiency nor power correction

The difference in this scenario, compared to Fig.49, is the absence of losses, thus $\eta = 1$ for both charging/discharging. However, $P_{cor} = 0$. The energy balance, is fluctuating out of the normal boundaries, within $+200$ kWh and $-400$ kWh. In order to charge and discharge throughout the whole period and be able to accommodate the needs of the energy balance, a battery with 400 kWh nominal capacity would be required.

![Figure 53: SOC limits, without efficiency and without allocated correcting power](image)
5.4.3 Effect of the power correction in Denmark and in GB

The energy balance of the battery, taking into consideration the different energy content and the regulation capacity $P_{\text{cap}}$, for the cases in GB and Denmark are shown below. In Fig. 54 the range of energy balance fluctuates between -10 kWh and +15 kWh. So for a 40 kWh battery nominal capacity with an initial SOC of 50% it corresponds to a SOC range of 10 - 35 kWh. In this simulation an efficiency of $\eta = 0.9$ is considered, both for charging and discharging. Both scenarios are realistic for an EV with the chosen battery size and within the limits by respecting the SOC constraints.

The reason that the $P_{\text{cap}}$ in Denmark is different compared to GB, lies in the different energy contents of their frequency. In order to remain within the desirable SOC limits an allocation of $P_{\text{cor}}$ equal to 3 kW is required in Denmark, while 2 kW is an adequate amount of power correction in GB. Overall, the results are similar for both cases.

![Figure 54](image)

Figure 54: (a) SOC limits GB with 8 kW power regulation and 2 kW power correction. (b) SOC limits DK with 7 kW power regulation and 3 kW power correction.

5.5 Yearly energy throughput

The yearly energy throughput is the amount of energy that cycles through the storage bank in one year. Throughput is defined as the change in energy level of the battery, measured after the efficiency losses.

The formula that calculates the energy throughput is as follows. The absolute value of the power used for charging/discharging is symbolized with $P_{\text{bat}}$.

$$E_{\text{energy throughput}} = \sum_{t=0}^{365} |P_{\text{bat}}| \cdot t$$  \hspace{1cm} (24)

The following figure shows the distribution of the total energy throughput caused by the driving behaviour of the EV owners and the energy from delivering frequency regulation during one year in Denmark. The allocated power for correction is 3 kW and the power capacity for frequency regulation is 7 kW.
From Fig. 55 it can be observed, that the distribution of the yearly energy throughput only for driving is on average 3.13 MWh per vehicle and for frequency regulation is 11.11 MWh per vehicle, while the total amount is on average 14.23 MWh, per vehicle. Meaning that there is an increase of approximately 3.53 times when the energy required for driving is added to the energy used for frequency regulation.

Figure 55: Distribution of the yearly energy throughput

5.5.1 Comparison with the energy throughput in GB

The results of the yearly energy throughput in Denmark and in GB, are shown below. Fig. 56 shows the difference in the energy used to frequency regulation for a whole year, between GB and Denmark. Overall, the energy throughput in Denmark is larger, caused by the larger amount of energy used for frequency regulation, since the driving profile is the same in both scenarios. This dissimilarity lies in the fact that different set of rules are applied within these two countries. In GB the frequency response should be delivered in four-hour blocks per day, in order to get paid, while in Denmark the time constraints regarding the service provision are less strict, as it was described earlier in section 2.4.

In GB, there is an increase of 3.10 times on average, when going from just driving to also delivering frequency regulation, compared to 3.53 times increase in Denmark. The yearly energy throughput of the battery for driving remains the same. The energy throughput for frequency regulation in GB is on average 6.7 MWh per vehicle per year, while for both driving and frequency regulation is 9.8 MWh on average per vehicle. Thus the yearly average value of the total energy throughput in GB is 5 MWh less compared to Denmark.
5.5.2 Charging cycles during one year

The charge cycles is the number of complete charge/discharge cycles of the battery. Considering a battery with 40 kWh capacity, the total number of charge cycles can be estimated.

The number of charging/discharging cycles is calculated based on Eq. 25.

\[
\text{cycles} = \frac{\text{Energy throughput (kWh)}}{2 \cdot 40 \text{ (kWh)}}
\]  

(25)

Fig. 57 illustrates the distribution of the total number of charging cycles for every EV during one year in Denmark, taking into account the energy throughput calculated on section 5.5. Considering SOC limits of 20% - 90%, with a minimum number of 14 cycles and a maximum number of 304 cycles per year, it can be observed that the variance from the mean is high. High number of charging/discharging cycles results in a higher cycle ageing of the battery. The large difference between the number of charging cycles from one EV to another, can be explained from the dissimilarities of driving and charging behavior within the EVs in the sample. The parameters that affect the number of energy throughput and consequently the number of cycles, is once again the driving trips, charging and the FCR-N procurement.

Figure 57: Total number of charging cycles for 7163 EVs, during one year period. \( \sim N(\mu=177 \text{ cycles, } \sigma = 39.71). \)
A scientific study with a similar setup was carried out, to quantify the impact of normal driving and frequency regulation service and it was found that 182 full equivalent cycles, result in 2% capacity loss in five years or 0.4% per year\[13\]. Thus the results found in Fig[57] show that 177 cycles per year can only cause a negligible capacity loss. However, the total number of cycles can be doubled depending on the EV usage.

5.6 Capacity payment

The revenue when frequency regulation is delivered all full hours that the EV is at the household and not charging, are calculated. Normally, all accepted bids in the reserve market, will receive payment corresponding to the price requested by the supplier (pay-as-bid) and only the highest bid is published. However, for simplicity in this model it is considered that all the bids are accepted and all the EVs are receiving the same amount of payment, according to the highest accepted bid, which results in higher revenue.

**In Denmark:**

The capacity payment for FCR-N in Denmark is compensated per MW per hour when the service is made available. The average price for the specific hours during a whole year is seen in Fig[12]. It is obvious that the trend is similar in the depicted years. The prices are higher during the morning hours, from 1 a.m. to 6 a.m. These fluctuations are strongly correlated with the demand and supply at each hour of the day. The lower prices in 2016 and 2017 can be explained by a larger production compared to 2018. The prices of 2018 are observed to be relatively high, for this reason, the following simulations related with the calculation of the revenue based on the FCR-N, are calculated with the actual prices of the specific hours during 2017 since they can give a more realistic result.

The capacity payment is calculated based on the following formula:

\[
Revenue_{reg} = \sum_{h=1}^{8760} p_{reg,h} \cdot P_{r,h}, \text{ per hour}
\]  

\(p_{reg} = \text{price for frequency regulation}\)

**In GB:**

As it was described in 2.6 the capacity payment in GB is is received only if the EV is available 4 hours consecutively. The price for FFR \(p_{reg}\) in GB is considered fixed and is delivered in 8 £/MW per hour or 8.91 €/MW, per hour. Due to the margin in regulation prices but also the different hourly contracts for availability payment, between Denmark and GB, the final revenue would differ significantly.
5.7 Cost Vehicle-to-Grid (V2G)

In case the average system frequency is biased, the EV owner receives an hourly payment for the provision of grid services. Meaning, that there is an energy exchange between the EV and the grid, in order to facilitate the problem of the $E_{bias}^h$. Normally, the payment for this settling is determined by the upward and downward prices. In case of over-frequency the energy received from the grid is sold in down-regulation price, whereas in case of under-frequency the energy flows from EV to the grid is paid in up-regulation price (see section 2.5). However, in the following calculations the payment is settled based on the spot price every hour and the industrial tariffs. The spot prices are the same for the whole hour, even though the frequency measurements are every 15 minutes. Additionally, it is assumed that there is a scheme where the tariffs paid for charging are refunded when discharging.

The calculation of the cost in Denmark and GB is calculated as follows:

$$Cost_{V2G} = \sum_{h=1}^{8760} E_{grid}^h \cdot (\lambda_h + tariff_{industry})$$  \hspace{1cm} (27)

$E_{grid}^h = \text{energy exchange between grid and EV.}$

Finally, the costs are subtracted from the revenue to calculate the yearly profit. The results for both Denmark and GB are derived, from the following equation:

$$Profit = \sum_{h=1}^{8760} Revenue_{reg,h} - \sum_{h=1}^{8760} Cost_{V2G,h}$$  \hspace{1cm} (28)

5.8 Calculation of revenue and profit in Denmark

The revenue is a product of frequency regulation while the EVs are parked at home. The reason is that doing frequency regulation at work would require more V2G chargers and although the cost of the chargers is not included in the calculations, it was considered unrealistic to provide services while the EV is parked at work.

The simulation that calculates the revenue in the following Fig.58 is taking into account the conversion losses but also the allocated power for correction. In this way the SOC constraints are respected. The $P_r = 7 \text{ kW}$ is the assigned capacity for FCR-N while $P_{cor} = 3 \text{ kW}$ is the allocated power for the SOC correction. The results are shown below.
Figure 58: (a) Distribution of the yearly revenue by charging at home and at work, with efficiency and with allocated correcting power (b) Distribution of the yearly revenue and profit by charging at home, with efficiency and with allocated correcting power.

The distribution of the revenue is shown in Fig.58 ranging from 100 - 1400 € per year, with an average value of 923 € per year. The EVs that provide frequency regulation for most hours have the highest energy loss, so the remaining profit after subtracting the individual charging cost has a lower spread between 50 and 1200 € per year. The average cost of the yearly energy losses is 10% of the revenue and result in an average profit of 828 € year. However, considering an efficiency equal to 95%, the cost of the energy losses goes down by 50%.

In the following scenario the distribution of revenue when $\eta = 0.9$ is taken into account but without allocated correction, $P_{cor} = 0$, is presented.

Figure 59: (a) Distribution of the yearly revenue by charging at home and at work, with efficiency but without allocated correcting power. (b) Distribution of the yearly revenue and profit by charging at home, with efficiency but without allocated correcting power.

The distribution of the revenue in this case has a larger spread. The revenue varies from 200 - 2000 € per year. Although, the EVs provide frequency regulation the same amount of hours, they have higher revenue, since the $P_r = 10$ kW. However, the physical constraints of SOC are violated, as it can be seen from Fig.49. For this reason, this scenario is unrealistic, because in a real case situation the battery of the EV would be depleted and thus it would be unable to provide services.

68
5.8.1 Comparison between Denmark and GB.

A visual representation of the results in the revenue between Denmark and GB is depicted in the following figure. While in Table.17 the revenue along with the cost for V2G and the profit are compared, for both countries.

In Fig.60 is shown the results of revenue and profit in GB and Denmark respectively.

![Figure 60: (a) Distribution of the yearly revenue and profit by charging at home, with efficiency and with allocated correcting power in GB. (b) Distribution of the yearly revenue and profit by charging at home, with efficiency and with allocated correcting power in Denmark.](image)

The results in Denmark were described in Fig.58. In GB the revenue spreads from 100 - 600 € per year, with an average value of 319 € per year. Although, adding the cost of the energy losses, the average profit results in 226 € per year.

The results of all the scenarios are presented in Table.17.

5.8.2 Results

<table>
<thead>
<tr>
<th></th>
<th>Base case DK</th>
<th>Base case GB</th>
<th>DK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\eta = 0.9$</td>
<td>$\eta = 0.9$</td>
<td>$\eta = 0.9$</td>
</tr>
<tr>
<td></td>
<td>$P_{\text{cor}} = 3,\text{kW}$</td>
<td>$P_{\text{cor}} = 2,\text{kW}$</td>
<td>$P_{\text{cor}} = 0$</td>
</tr>
<tr>
<td>Revenue €</td>
<td>923</td>
<td>319</td>
<td>1318</td>
</tr>
<tr>
<td>CostV2G €</td>
<td>94</td>
<td>92</td>
<td>53</td>
</tr>
<tr>
<td>Profit €</td>
<td>828</td>
<td>226</td>
<td>1265</td>
</tr>
</tbody>
</table>

Table 17

Table.17 shows the average values of the revenue, cost from V2G and profit, for the base case in Denmark and GB as well as the scenario in Denmark where the $P_{\text{cor}}$ was not considered. Although in the latter case the average value of revenue in Denmark are significantly higher, the SOC constraints are not respected (see Fig.53) and thus the results are not realistic. Finally, the large difference in revenue between the cases in Denmark and the case in GB lies to the fact that the EV in GB has to be available four consecutive hours in order to receive the availability payment, as seen in section 2.6. On the other hand, the EV in Denmark has to be
available at least one hour. These 4-hour block contracts along with the low prices for frequency regulation, are the main reasons of this difference between the revenue in two countries.

5.9 Implementation of different scenarios

The differences between the cases in Denmark and GB, have resulted in different revenues as it was already observed in Table 17. At this point, it would be interesting to see the effect of the different energy content of GB’s grid frequency but also the unique pricing strategy in GB, implemented in Denmark. For this reason, different scenarios are simulated and the results are presented below.

- **Base case**: The base case scenario in Denmark as seen in Fig 58.
- **Fixed regulation price**: In this scenario instead of using the FCR-N price, a fixed price = 8.91 €/MW per hour is used just like the GB pricing strategy.
- **4-hour blocks**: Instead of 1-hour the EV has to be available for frequency regulation 4 consecutive hours in order to receive the FCR-N payment.
- **GB_{energy con.} & P_r = 8 kW**: In this simulation the GB_{energy con.} along with P_r = 8 kW, is implemented on the base case scenario.
- **Upward & Downward regulation prices**: The up- and downward regulation prices are used, instead of the spot price, for the hourly energy exchange due to the existence of the energy content. However, it should be mentioned that the effect of losses results in a higher amount of energy injected from the battery to the grid, when there is under frequency. Those losses should be paid in the spot price instead, but the difference wouldn’t be significant since the spot prices are similar with the up-regulation prices (see Fig 15).

   The following Table 18 shows the revenue, cost and profit for different cases. The simulations ran with one parameter change at a time. The evaluation of the average value of revenues, profit and cost, can show in what scale the changes that are chosen, can affect the outcome. Additionally, the average number of hours the EVs were available to provide frequency regulation when they were parked at home, are depicted.

```
<table>
<thead>
<tr>
<th></th>
<th>Base case DK</th>
<th>GB fixed regulation price</th>
<th>4-hour blocks</th>
<th>GB_{energy con.} &amp; P_r = 8 kW</th>
<th>Upward &amp; Downward prices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenue (€)</td>
<td>923</td>
<td>321</td>
<td>819</td>
<td>923</td>
<td>923</td>
</tr>
<tr>
<td>Cost_{V2G} (€)</td>
<td>94</td>
<td>94</td>
<td>82</td>
<td>65</td>
<td>68</td>
</tr>
<tr>
<td>Profit (€)</td>
<td>828</td>
<td>227</td>
<td>736</td>
<td>860</td>
<td>854</td>
</tr>
<tr>
<td>Availability (h)</td>
<td>5158</td>
<td>5158</td>
<td>4624</td>
<td>5158</td>
<td>5158</td>
</tr>
</tbody>
</table>
```

Table 18
The calculations for the Cost_{V2G} in the case where the upward and downward regulation prices used, is derived from the following:

If, $E_{bias}^h < 0$:

$$V2G_{dis} = \sum_{h=1}^{8760} E_{dis,reg}^h \cdot (p_{up}^h + \text{tariff}_{industry})$$  \hspace{1cm} (29)$$

If, $E_{bias}^h > 0$:

$$V2G_{ch} = \sum_{h=1}^{8760} E_{ch,reg}^h \cdot (p_{down}^h + \text{tariff}_{DSO})$$  \hspace{1cm} (30)$$

$E_{bias}^h$ = energy content of the system, $E_{dis,reg}^h$ = energy injected to the grid only from frequency regulation (has a negative (-) sign), $E_{ch,reg}^h$ = energy stored in the battery only from frequency regulation.

$$Cost_{V2G} = V2G_{dis} + V2G_{ch}$$  \hspace{1cm} (31)$$

Calculation of the Cost_{V2G}, with the distribution network tariffs

Under the circumstances of a more realistic approach, a final scenario was simulated. In this case the cost derived from the energy losses due to FCR-N provision, is not calculated with the industrial tariffs, obtained from section 2.7, which is equal to 0.03 € per kWh. Instead the tariff paid on DSO is used for the calculation. According to EL-NET Øst the tariff is equal to 0.0376 € per kWh[44]. Additionally, the energy losses paid when the EV is discharging, are not compensated with the same price.

The Cost_{V2G} is calculated based on the following equations.

If, $E_{bias}^h < 0$:

$$V2G_{dis} = \sum_{h=1}^{8760} E_{dis,reg}^h \cdot p_{up}^h$$  \hspace{1cm} (32)$$

If, $E_{bias}^h > 0$:

$$V2G_{ch} = \sum_{h=1}^{8760} E_{ch,reg}^h \cdot (p_{down}^h + \text{tariff}_{DSO})$$  \hspace{1cm} (33)$$
Final Cost\(_{V2G}\):

\[
Cost_{V2G} = V2G_{dis} + V2G_{ch}
\]  \hspace{1cm} (34)

It is estimated that the Cost\(_{V2G}\) will be increased and consequently the final profit will be reduced. The results are presented in the following Table.19.

<table>
<thead>
<tr>
<th>Results</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenue (€)</td>
<td>923</td>
</tr>
<tr>
<td>Cost(_{V2G}) (€)</td>
<td>172</td>
</tr>
<tr>
<td>Profit (€)</td>
<td>751</td>
</tr>
</tbody>
</table>

Table 19

As it can be seen, the assumption was correct. The average value of the Cost\(_{V2G}\) is 172 € per year, which results in a final profit of 751 € per year. To sum up, using the current pricing system the final profit for the EV user will be reduced on average, by 77 € per year. However, if the payment regulation changes in the upcoming future, the EV owner will have the chance to be reimbursed for the energy losses.
5.10 Estimation of the availability of EVs

The availability of the EVs, when they are located at home and are available to provide frequency regulation is known from section 5.2. Based on this availability, the probability within a certain range, that a sample of EVs are available to provide FCR-N will be calculated. The probability is based on two possible outcomes labelled by n=0 and n=1. In which n=1 ("Available") occurs with probability p and n=0 ("Not Available") occurs with probability q=1-p. Since the output is binary, the average value of all the EVs, for every 15 minutes, during a whole year, needs to be calculated so that the different percentile bands can be found.

A theoretical statistical analysis is made based on the average value of the availability of 7163 EVs. It was found that the usage of all the weekdays and weekends was similar, so they can be represented together as an average weekday or weekend. The fact that a part of the EVs are available on average during the working hours represents a potential optimization in the revenue.

Fig. 61 shows with a certain probability the percentage of vehicles that are available to provide services to the grid, during 24 hours. The median signifies that centre point of the data, in other words it represents the 50% or 0.5 percentile, which means that it splits the data into two groups that contain the same number of data points. The y axis shows the share of EVs, that are available, with a certain probability. For the weekdays (a), the fact that a large sample of the EVs are available during the working hours represents a potential to increase the revenue by utilizing more vehicles, during these hours. The second figure (b), shows a similar representation of the percentile bands, during the weekends. As it can be seen the interval of the different percentiles is smaller and thus the uncertainty is less.
Figure 61: (a) Percentile plot of plugged-in cars available for FCR-N, on weekdays, based on measurements of 7163 EVs for a time period of one year. (b) Percentile plot of plugged-in cars available for FCR-N, on weekends.

As it can be observed, the share of the EVs that are disposable to provide frequency regulation during day time on week days, is fluctuating within 20% - 55%, while on weekends it ranges between 50% - 65%, for a confidence interval of 99%. A higher percentage means that there is the possibility of a higher share of EVs to be available, during week days. As an explanation can be given the fact that during these hours on week days, the most of the EVs are either driven or they are not parked at the household. Thus they are not available for service provision.

Fig 62 shows the actual limits of each percentile during a time period of 24 hours, which means that the max and min limits of the actual measurements without adding the standard error where used. Thus each percentile appears to be smaller, compared to Fig 61 which lowers the uncertainty. Since the distribution of the sample is biased, the calculation of the percentile bands in that way is more accurate.
To conclude, the concept that the EVs can be seen as a group with certain statistical properties was demonstrated. Based on these properties the EV aggregator can submit a bid with certain confidence, in the reserve market.
5.11 Analysis of high revenue EVs

The availability of EVs with revenue higher than 1000 €, is shown below. The fleet of the high revenue EVs consists of 501 out of 7163 EVs, which is approximately the 7% of the total sample.

The blue line illustrates the share of EVs with yearly revenue more than 1000 €, which corresponds to the 7% of driving data set, or 501 out of 7163 EVs, while the orange line represents the share of the total number of EVs. As it can be observed, during a one week period, the share of the high revenue EVs has an availability rate that ranges between 70% - 95% during weekdays and between 80% - 95% during weekends. On the other hand, the availability rate of the total number of EVs during weekdays varies between 35% and 80%, while during weekends the lower limit increases to almost 60% with the higher limits remaining at 80%.

Figure 63: Availability of plugged in EVs on weekdays with the highest revenue.

Fig. 64 shows the availability rate, with a certain confidence, but only for the 7% of the 7163 EVs. This percentage represents the most profitable vehicles, during week days and weekends. During weekdays the average value of 501 EVs that are able to provide services during morning hours is within 90% - 100%, while during night hours the percentage ranges between 80% to 100%.

During weekends the share of the EVs is higher during morning and night hours, ranges between 95% - 100%, while during the day it varies between 80% - 90%.
Figure 64: (a) Availability of EVs for frequency regulation, on weekdays, based on measurements of 501 EVs for a time period of one year. (b) Availability of EVs for frequency regulation, on weekends, based on measurements of 501 EVs for a time period of one year.

As it can be observed in Fig.64 the upper endpoints of the highest degree confidence intervals for the share of EVs is greater than 100% during night hours, on week days. Thus it is legitimate to say that the upper endpoint should have a bound at 100%.

The way the confidence intervals (see Eq.14) are calculated, contains the assumption that the sample follows a (Z-) normal distribution, instead of a skewed or in some way non-normal distribution. For this reason, this procedure could lead to intervals for which particular estimates are outside the 0% - 100% limits.

Fig.65 depicts the different percentiles with their actual min and max limits, for the availability of the top 501 most profitable EVs. As it can be seen, in this case the upper limits of the 90th percentile do not exceed 100%.

In general, the availability of the EVs with revenue more than 1000 € per year, tends to be higher than the case where the availability of all the EVs is presented, see Fig.62. The fact that
a smaller sample is used in this case, increases the impact of the individual EV in the group’s capacity.

![Graph](image)

Figure 65: (a) Availability of EVs for frequency regulation, on weekdays, based on measurements of 501 EVs for a time period of one year (measured). (b) Availability of EVs for frequency regulation, on weekends, based on measurements of 501 EVs for a time period of one year (measured).
Fig. 66 shows the revenue along with the profit of the 7% of the most profitable EVs. The distribution of the revenue varies from 1200 € - 1400 € per year. Although there is a small number of EVs (less than 5 EVs) with revenue more than 1400 € per year. The clear profit of the most profitable EVs ranges between 1050 € and 1250 € per year. The average values of revenue and profit for the investigated samples is 1265 € and 1129 € per year, respectively.

Figure 66: EVs with revenue greater than 1000 €. Total number of 501 EVs.

5.12 EV penetration in Denmark

The total number of personal vehicles in Denmark, according to Danmarks Statistik, is 2.5 million, while the share of EVs is only 5% (250,000 EVs) of the total number of vehicles.

<table>
<thead>
<tr>
<th>Year</th>
<th>All Denmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>2 216 217</td>
</tr>
<tr>
<td>2015</td>
<td>2 265 914</td>
</tr>
<tr>
<td>2016</td>
<td>2 322 921</td>
</tr>
<tr>
<td>2017</td>
<td>2 394 650</td>
</tr>
<tr>
<td>2018</td>
<td>2 458 012</td>
</tr>
<tr>
<td>2019</td>
<td>2 520 814</td>
</tr>
</tbody>
</table>

Figure 67: Stock of vehicles in Denmark from 2014 to 2019.

Fig. 68 shows the potential capacity provision, by utilizing a fleet of 11,250 EVs, which is a number that represents only 9% out of the total number of EVs (250,000 EVs) owned in Denmark. Based on the availability rate, of the EVs with revenue higher than 1000 € (see 63), the following results arise.
In order to meet the requirement for service provision in Denmark, 9% out of the total 250,000 EVs, have to be utilized. This number represents an adequate sample that can cover the needs for frequency regulation on a daily basis, as it can be seen from Fig. 68.

The power supplied during both weekdays and weekends is more than enough to cover the grid requirements in Denmark, which is 50 MW. Even during the hours when the availability is at its lowest point. The $P_{cap} = \pm 7$ kW since an allocated $P_{cor} = \pm 3$ kW is essential in order to remain within the desirable SOC limits.
5.13 Estimation of the FCR-N prices

It was found that the FCR-N prices of a given day \(d_i\) were similar with the prices of the previous day \(d_{i-1}\), so based on this observation the frequency regulation prices of the following day are predicted, considering the prices of the previous day, see Fig. 69 below.

![Frequency regulation price chart](image)

Figure 69: FCR-N price per hour, during March 4, 2017 (Saturday) and March 5, 2017 (Sunday).

In order to get a more realistic estimation, a function was built. This function compares the actual FCR-N prices with the predicted prices. Just like in the real market, the supply of the lowest bidder is the one that will be scheduled. Meaning that this function compares the hourly FCR-N_{\text{actual}} prices with the hourly FCR-N_{\text{predicted}} prices and every time the lowest price is accepted. For this reason, every time the FCR-N_{\text{actual}} prices are accepted into the market, the revenue for this specific hour will be zero. This zero value in the revenue will represent the penalty for making a guess.

\[
\text{FCR-N}_{\text{actual}} = \begin{bmatrix} d_i \\ \vdots \\ d_f \end{bmatrix}, \quad \text{FCR-N}_{\text{predicted}} = \begin{bmatrix} d_{i-1} \\ \vdots \\ d_{f-1} \end{bmatrix}
\]

To improve the chances that the predicted prices will be accepted, but at the same time, the best possible revenue will be obtained, a different strategy was implemented. Two more simulations are running, where the estimations, based on the values of the previous day, multiplied with a coefficient = 0.9 first and 0.85, afterwards. The outcome will result in higher revenues compared to the previous scenario, although it will be lower than the case where the actual prices used.
The coefficients 0.9 and 0.85 were chosen empirically, after running the simulation for several times, in order to find the best possible outcome. Decreasing the value of the coefficient more than 0.85 reduces the average value of revenue.

The results are presented on the following Table 20.

<table>
<thead>
<tr>
<th></th>
<th>Actual FCR-N prices</th>
<th>Predicted FCR-N prices</th>
<th>Predicted FCR-N prices (c = 0.9)</th>
<th>Predicted FCR-N prices (c = 0.85)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Revenue (€)</td>
<td>923</td>
<td>414</td>
<td>708</td>
<td>720</td>
</tr>
<tr>
<td>Accepted (%)</td>
<td>100</td>
<td>53</td>
<td>88</td>
<td>93</td>
</tr>
</tbody>
</table>

Table 20

The difference in the revenue between the base case scenario and the scenario where the prices are estimated, represents the penalty for making an attempt to estimate the future prices. The predicted prices that were not multiplied with a certain coefficient were not scheduled, half of the time. As it can be seen from the results, the estimation of the FCR-N prices, based on the values of the previous day, can result in 50% of the actual revenues.

On the other hand, by deploying a strategy where the estimations were multiplied with 0.9 and 0.85, the accuracy rises up to 88% and 93%, respectively.

To conclude, an interesting observation regarding the estimation of the future prices was made. Based on all the above mentioned, by bidding the prices of the previous day, multiplied with a coefficient of 0.85 results in a 93% accuracy, that the bids will be scheduled.
6 Optimization of charging and service strategy

An optimization strategy is formulated for every EV participating in the energy market. The aim of this strategy, is the maximization of the revenue for the EV users. The implementation deals with a different set of parameters. The spot price and the reserve capacity price signals, the energy content carried by the grid’s frequency as well as the charging power of the EV are considered the known inputs of the model.

The formulation was implemented in Python, using a high-level modelling solver called Gurobi, which is one of the most powerful mathematical optimization solvers that allows the implementation of Linear Programming (LP) and Mixed Integer Linear Programming (MILP), among others[45].

6.1 Description of the problem

The main objective is to optimize the revenue of each EV by minimizing the cost, while respecting a set of constraints related with the SOC limits and the power constraints of the V2G chargers. The prices for the frequency normal reserve but also the prices for the electrical energy traded in the day-ahead market, are provided. For this reason, it makes sense to optimize the schedule when the EVs are charging and providing frequency regulation services. As such the EVs are charging when the electricity price is low and provide frequency regulation when the capacity payment is high. It should be mentioned that the revenue is optimized for every individual EV profile. Additionally, the cost of the initial investment is not taken into consideration.

Once more the nominal power of the V2G chargers remain the same, with \( P_{nom} = 10 \text{ kW} \), while the nominal capacity of the battery, is \( Q_n = 40 \text{ kWh} \) and is the one that is used on the Nissan LEAF 2018. For the optimization, the charging/discharging losses are taken into account. As raised in previous chapters a constant charging/discharging efficiency, \( \eta_c = \eta_d = 0.9 \), is a good estimation for all loading levels.

For simplification of the implementation, the spot prices from the day-ahead market are used, instead of the upward and downward prices, for the hourly energy exchange between the EV and the grid. Whereas the FCR-N prices are used for the reserve market. The spot prices correspond to the actual prices for 2018 while the prices for capacity payment are from 2017 since 2018 had unusually high prices.

The time step (\( \Delta t \)) is one hour since the spot and FCR-N prices are updated hourly. During this hour the charging or the frequency service procurement is considered constant. Moreover, the time horizon, I, of the optimization is 8760 hours. Since \( \Delta t \) is one hour and the power for charging (\( P_c \)) is constant, the energy traded on the spot market the day-ahead is equal to \( P_c \).

For example buying 1 kWh, is similar as charging with \( P_c = 1 \text{ kW} \), the same hour. The same goes for discharging (\( P_d \)) since the charger is bidirectional the EV can also sell energy to the grid. Therefore, the cost function consists of three different parts. The part that calculates the cost, for the energy received from the grid, the part that calculates the revenue for the energy sold to the grid and the revenue that comes from the availability of the FCR-N. The energy price (spot\(_i\)) for the day-ahead market at Nord Pool is in \( €/\text{kWh} \) while the capacity payment (\( c_i \)) for FCR-N is in \( €/\text{kW} \) per hour.
6.1.1 Preparation of the parameters

The inputs of the spot and FCR-N prices are already in one hour blocks. Thus the energy content and the energy used for driving are merged into one hour blocks too. See Fig. 70.

All of the inputs are in form of vectors. The measurements of the energy content contain the conversion losses, considering an \( \eta = 0.9 \), while the measurements for driving consumption have already been calculated in chapter 5.1. The estimation of these losses is necessary to predict a realistic outcome that aligns with the SOC storage limits.

The outcome of the model, which represent the annual revenues, is expected to be better than the results obtained from the simulation of the holistic model in section 5.8.2. However, the results will be discussed further after the simulation of the model.

6.1.2 Setting up the constraints

The different parameters and the physical constraints are presented. The \( P_{\text{reg}} \) is the the same for upward and downwards regulation since FCR-N is a symmetric service.

One of the constraints that should be taken into account is that the EV cannot charge and discharge at the same time.

So the vectors for \( P_c \) and \( P_d \) of each EV, should be orthogonal, \( P_c \perp P_d \).

However charging and discharging the EV, at the same time is not profitable, even if the spot is low, due to the losses on the power converter. Therefore, because of the way the optimization problem works there is no need to add a constraint for the orthogonality of the \( P_c \) and \( P_d \) vectors.

The \( P_c \), \( P_d \) and \( P_{\text{reg}} \) can be represented in vector form, as follows.

\[
P_c = \begin{bmatrix} P_{c,1} \\ \vdots \\ P_{c,I} \end{bmatrix}, \quad P_d = \begin{bmatrix} P_{d,1} \\ \vdots \\ P_{d,I} \end{bmatrix}, \quad P_{\text{reg}} = \begin{bmatrix} P_{\text{reg},1} \\ \vdots \\ P_{\text{reg},I} \end{bmatrix}
\]
The different constraints related to \( P_c \), \( P_d \) and \( P_{reg} \), which is the power used for frequency regulation, can be described as follows:

\[
P_c \geq 0, \quad P_d \geq 0, \quad P_{reg} \geq 0, \quad P_{\text{max}} \geq \| P_{\text{reg}} + P_c + P_d \|_\infty
\] (35)

The infinity norm gives the maximum of the absolute value of the components of \( P_{\text{max}} \) vector.

The evolution of the SOC, also has to be modeled for the optimization. The SOC of the battery increases or decreases, according to the activity of the EV, every hour. The parameters that affect the SOC are \( P_c \), \( P_d \), \( E_{\text{drive}} \) which is the energy used for the driving trips and \( E_{fcr-n} \) as the energy exchange due to the energy content of that period.

It is also important to mention the the losses due to \( \eta = 0.9 \), for the \( E_{\text{drive}} \) and \( E_{fcr-n} \) are already included. The evolution of the SOC is given by the following equation:

\[
\sum_{i=0}^{I} SOC_{i+1} = SOC_i + [E_{\text{drive},i} + P_{\text{reg},i} \cdot E_{fcr-n,i} + P_{c,i} \cdot \eta - P_{d,i} \cdot \frac{1}{\eta} \cdot \frac{1}{Q_n}]
\] (36)

Moreover, constraints for the SOC have to be taken into account. The initial value of the SOC is considered known and is set to 50\% which corresponds to 20 kWh, for a battery with \( Q_n = 40 \) kWh. Additionally, for a better preservation of the battery’s health the recommended limits of operation are between 20\% - 90\%.

\[
SOC_1 = 0.5, \quad 0.2 \leq SOC_{i=0...I} \leq 0.9
\] (37)

Finally an additional constraint was necessary to implemented, that would restrain the model to use \( P_c \), \( P_d \) and \( P_{reg} \), while the EV is driven and thus the energy used for driving \( E_{\text{drive},i} \) is non zero.

\[
|P_{\text{cap},i=0...I}| \cdot E_{\text{drive},i=0...I} = 0
\] (38)

\[
|P_{c,i=0...I}| \cdot E_{\text{drive},i=0...I} = 0
\] (39)

\[
|P_{d,i=0...I}| \cdot E_{\text{drive},i=0...I} = 0
\] (40)

However, to put into effect these constrains the use of binary values was required. The combination of non discrete decision variables with binary variables is known as Mixed-Integer Linear Programming problem.

The main objective of the optimization, is the minimization of the cost function. It consists of the sum of the charging cost minus the revenue from selling energy to the grid and providing FCR-N. The charging cost for every EV is calculated as the product of \( P_{c,i} \) and the electricity...
price ($\lambda_i$) during this period. Also the revenue from $P_{d,i}$ is calculated with the spot, and the revenue from the reserve market is calculated based on the FCR-N price ($c_i$).

$$\min \sum_{i=0}^{I} \lambda_i \cdot P_{c,i} - \lambda_i \cdot P_{d,i} - c_i \cdot P_{reg,i}$$

s.t.

$$P_c \geq 0, \quad P_d \geq 0, \quad P_{reg} \geq 0, \quad P_{max} \geq \|P_{reg} + P_c + P_d\|_{\infty}$$

$$SOC_{i+1} = SOC_i + [E_{drive,i} + P_{reg,i} \cdot E_{fnr,i} + P_{c,i} \cdot \eta - P_{d,i} \cdot \frac{1}{\eta}] \frac{1}{Q_n}$$

$$SOC_1 = 0.5, \quad 0.2 \leq SOC_{i=0..I} \leq 0.9$$

$$|P_{cap,i=0..I}| \cdot E_{drive,i=0..I} = 0$$

$$|P_{c,i=0..I}| \cdot E_{drive,i=0..I} = 0$$

$$|P_{d,i=0..I}| \cdot E_{drive,i=0..I} = 0$$
6.2 Results

Fig. 72 shows the prices from 1\textsuperscript{st} until 2\textsuperscript{nd} of January. During the same period, Fig. 74 shows the optimal schedule for charging and service provision of one EV. The schedule’s objective is to minimize the cost function, seen in Eq. 41. From Fig. 74 it is obvious that the $P_{\text{nom}}$ of the charger, is distributed equally between charging/discharging and service provision, during these 24 hours.

The service procurement is done during the hours that the FCR-N prices are high, while the charging/discharging is done when the spot prices are low/high respectively. The SOC of the battery remains within the desirable limits [20\% - 90\%], respecting the set of constraints.

![Figure 72: Illustration of Spot price and FCR-N price, during 1\textsuperscript{st} of January.](image)

Figure 73
Figure 74: Schedule of optimal charging and service provision during 1st of January.

Most of the time all 10 kW are used for service provision, unless a part of $P_{nom}$ is needed for charging/discharging. In general, selling energy is not profitable since the electricity prices do not vary a lot. However, if there is a steep decrease in the spot price, the EV will discharge and take advantage of it. Due to the conversion losses, it is not profitable to charge and discharge all the time since a big share of $P_{nom}$ is required and that would curtail the available power for frequency regulation.

During the first 24 hours the EV is not driven.

Fig. 75 shows the distribution of the SOC, during one year period, as a result of the charging/discharging schedule with $\eta = 0.9$ in both directions but also the service provision schedule. Although the average value is 52%, in many cases SOC has reached its lower limit.
The results for a simulation running for one year, are shown in the following Table 21. The economic terms as a result of FCR-N provision and charging/discharging are depicted. Based on the optimized schedule and prices the yearly income from service provision is 1813 € per year. The income from FCR-N payment is considerably higher compared to the results seen in Fig. 66. However, a 24 hour availability service both for week days and weekends is considered, which in reality is less as it was seen on section 5.10.

The offset between charging and discharging results in a profit of 140 €, in the spot market. The amount of savings on the spot market comes from the consumption when the electricity prices are low. However, a better estimate of the charging cost would be given if the average value of the domestic tariff was included in the spot market price, which is 0.26 €/kWh in Denmark, as seen on section 2.7. The yearly driving consumption is 3651 kWh, which results in 18.2 k km per year, for a average driving consumption of 0.2/kWh and is close to the average yearly driving distance in Denmark 3.3.1.

<table>
<thead>
<tr>
<th></th>
<th>FCR-N Payment [€]</th>
<th>Charging Cost [€]</th>
<th>Discharging Income [€]</th>
<th>Driving Consumption [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly</td>
<td>1728</td>
<td>-117</td>
<td>247</td>
<td>3651</td>
</tr>
</tbody>
</table>

Table 21: Optimization results

Adding the tariff_{domestic} = 0.26 €/kWh for charging on the spot market price, would result in a yearly retail cost of 974 €. This cost would significantly reduce the final profit of the EV owner at 1001 € per year. This assumption is made to point out the impact of the additional charges on the spot market price. By including the domestic tariff, into the optimization model, the result of the optimized charging schedule would be different.

According to the result obtained from the model formulated on section 5.2, the income from the FCR-N payment for the same EV was on average 1100 € per year, which means that the optimized schedule resulted in 628 € more revenue per year. However, it should be mentioned that the \( P_{reg} \) for service provision in that case was 7 kW, while in the optimization model a
maximum 10 kW is used. The simulation ran for several EVs but the results of only one are depicted. The EV chosen has a yearly driving distance close to the average driving distance for personal vehicles in Denmark, thus it is a representative example. In all cases (7163 EVs), the FCR-N prices, spot market prices and energy content are the same, while each EV has its own yearly driving consumption which is close to the yearly average driving consumption for every vehicle in Denmark. Additionally, the restrictions of the defined constraints are the same for all EV profiles.

6.3 Conclusion

The optimized schedule for service provision, for all the EVs, results in a high income which is too optimistic. The only limitation for FCR-N service, is the capacity of the charger, with a max ± 10 kW V2G charger. The actual availability profile of the EV is not considered. In a realistic case, the EV is not available to provide services to the grid, all the time during weekdays and weekends, but only when it is parked at the household. However, considering a case where the EV is plugged-in, even if it is located at work, the results would be more convincing.

Additionally, in many cases the SOC is very low, close to 8%, which is the defined lower bound of the SOC in the optimization problem. In the simulated scenario the driving consumption but also the time of the upcoming trip is known. However, that is not the case in a real scenario, as the EV owner can drive off at any time. Considering this, the EV’s battery might not have enough energy to accommodate the needs of an upcoming long trip.

Concluding, based on the historic data possessed for charging and driving, the precision of the plug-in and plug-out time can be added to the model for a better estimation of the revenue.
7 Conclusions and future work

7.1 Conclusions

In this section the results are concluded, answering the question outlined on section 1.4.

- What is the effect of the biased frequency and the efficiency losses on service provision with EVs?

Taking consideration of the energy content carried by the biased frequency, is essential for respecting the physical constraints related with the SOC of the battery. The distribution of the energy content, can show with a degree of uncertainty, the amount of energy required to accommodate the needs for frequency regulation. By violating the constraints of the SOC, the EV become unable to provide FCR-N with liability.

Additionally, the efficiency losses due to charging and discharging should be taken into account. The efficiency of the 10 kW bidirectional charger is the same in both directions, \( \eta_c = \eta_d \). Since the commitment is from the AC side, the EVs as FCR-N providers should deliver more energy, in order to offset the efficiency losses and that affects the battery’s SOC.

The high variance of the energy content in addition with frequency regulation procurement for long periods can lead in depletion of the battery, if the right measurements are not taken into account. However, it was found that allocating a share of the V2G charger’s capacity for power correction, the SOC problem can be solved. The \( P_{\text{cor}} \) is applied when the energy balance of the battery leaves the acceptable window during FCR-N provision. This strategy reduces the available capacity for FCR-N but helps the SOC to remain within the desirable limits.

FCR-N is an availability payment service and as a result the revenue due to this strategy will decrease, at the same time the EV will be able to provide services without any hindrance throughout the whole period.

The investigation of both the energy content of the system’s frequency and the converter’s losses are essential for allocating the proper amount of capacity for service provision.

- Is the utilization of an EV as a single unit or an EV fleet for FCR-N provision in the Danish market under the Transmission System Operator profitable?

The driving and charging pattern during one year for 7163 EVs was analyzed, Which made possible the calculation of the potential grid services of each EV user. Taking into consideration a V2G charger of 10 kW, it was found that an EV with 40 kWh battery capacity, can provide services with 7 kW regulation capacity while the remaining 3 kW are used to maintain the SOC within the acceptable limits. The time periods were calculated when the EVs are driving, charging or parked at the household and thus are available to provide services to the grid. The revenue due to FCR-N provision vary for every EV with a maximum value around 1400 € per year, while on average the revenue is 923 € per year. The cost of V2G including the efficiency losses has an average value of 94 € per year, considering the calculation with the TSO tariff. If the tariff of DSO is taken into account the cost of V2G rises up to 172€ per year.
The average yearly energy throughput as a result of driving and service provision is 14.23 MWh per year and corresponds to an average value of 177 full equivalent charge cycles, which can be twice for several EVs depending on the usage. Overall, the earnings performing FCR-N are beneficial for the EV owners but they also depend on the availability of each EV to deliver the service. Finally, the cost of the V2G charger is not included and since the service provision is done at home it might weight upon the EV owner.

- Is it possible to estimate the availability of the EVs for service provision but also the frequency regulation prices when they are not known?

A statistical analysis was made in the section 5.10 that calculated the probability at least a certain percentage of EVs to be available for ancillary service provision, during week days and weekends. Considering a large number of samples as the one that is acquired from Nissan, the result of this analysis can be used to make a bid of an EV fleet with a certain confidence. Furthermore, a function was build in the section 5.13 that allowed the estimation of the FCR-N prices, based on the values of the previous day. More specifically, showing that there is a strong correlation between the FCR-N prices of two consecutive days, a bidding strategy that can predict the prices of the next day was implemented. Being able to predict the future prices with a certain accuracy, can improve the bidding strategy on the day-ahead market.

- Can an optimized charging and service provision schedule that respects a set of physical constraints, result in higher revenue for the EV owner?

An optimization model was demonstrated in chapter 5.13 that maximizes the yearly revenue of the EV owner from FCR-N payment. At the same time the EV owner had a chance to participate in the electricity market and take advantage of cheap charging when the spot prices were low. The optimization problem was formulated in Python and the solving was achieved with the use of Gurobi. A keen reader will realize that the optimization is to a certain extent naively formulated in terms of the service provision and charging schedule. The reason is that the EV owner can provide frequency regulation services or charge at any time, depending on if it is beneficial or not, ignoring the actual plug-in time, which makes it too optimistic. A more realistic scenario that contains the actual availability of the EV could be implemented. Although, such an attempt would increase the complexity of the optimization problem. In general the results of the simulation are acceptable and close to the real ones, considering an optimized schedule for both charging and service provision. Finally, the SOC limits of the battery, as well as the capacity limits of the charger, are respected throughout the investigated period.
7.2 Future Work

The purpose of this section is to outline several topics that were not covered in the course of this thesis:

- The availability of the EVs when they are parked at workplace was not included in the service provision schedule. A consideration of public chargers that can be used during these hours would potentially result in higher revenue.

- The Time of Use Tariffs (TOU) were not included in the electricity prices. An optimization where the TOU tariffs are taken into account in combination with frequency regulation could be of particular value for the calculation of the final profit.

- In the charging model formulated on section 5.1 the idea of smart charging could be implemented. Optimizing the way of charging, the EV owner could make additional profit from the participation in the electricity market.

- All of the simulations were performed for an EV model with 40 kWh battery capacity. An implementation with larger EV storage would decrease the time for charging, meaning that EVs have more time to perform frequency regulation.

- In this thesis, the business model evaluated the cost of energy losses, considering a V2G charger with 10 kW power capacity and 90% efficiency. It would be interesting to see the results of the earnings with a converter’s efficiency equal to 95%.
8 Appendix

8.1 Python code

8.1.1 Calculation of driving trips

```python
import numpy as np
import time
import copy

def calTripStart(driving_original):
    # last 15 minute before trip starts
    driving = copy.deepcopy(driving_original)
    tripWillStart = np.argwhere(np.logical_and((driving[1:] >= 101), (driving[:-1] <= 101)))
    tripStartEV = tripWillStart[:, 1]
    tripStartTime = tripWillStart[:, 0]

    # Check if a second trip follows the first
    twoTrips = np.argwhere(np.logical_and(np.logical_and(np.logical_and((driving[1:] >= 101), (driving[:-1] >= 101)), (driving[1:] != driving[:-1])), driving[:-1] <= 101))
    twoTripsEV = twoTrips[:, 1]
    twoTripsTime = twoTrips[:, 0]

    driving[twoTripsTime, twoTripsEV] += driving[twoTripsTime + 1, twoTripsEV] - 100

    return tripStartTime, tripStartEV, driving
```

8.1.2 Calculation of driving consumption

```python
def calDriveConsumption(driving_original, tripStartTime, tripStartEV, eta):
    consumption1 = np.zeros(driving_original.shape)
    consumption1[[tripStartTime], [tripStartEV]] = -(driving_original[[tripStartTime + 1], [tripStartEV]] - 100) / (5 * eta)  # Compensate for efficiency calculation
    return consumption1
```

8.1.3 Calculation of charging

```python
def calCharge(driving_original, consumption_original, tripStartTime, tripStartEV, eta):
    driving = copy.deepcopy(driving_original)
    consumption = copy.deepcopy(consumption_original)
    chargeTime = np.ceil(-consumption[[tripStartTime], [tripStartEV]] / (2.5 * eta * eta))[0]
    startCharge = (tripStartTime - chargeTime).astype(int)
```

for x in range(len(tripStartTime)):
    driving[startCharge[x]:tripStartTime[x],tripStartEV[x]]=10
    consumption[startCharge[x]:tripStartTime[x],tripStartEV[x]]= ...
    -consumption[tripStartTime[x],tripStartEV[x]]/chargeTime[x]/(eta*eta)
return consumption, driving

8.1.4 Allocation of Frequency Regulation

def allocateFFR(driving_original,consumption_original,energy_original,regulationPower):
    tic1=time.time()
    energy = energy_original*regulationPower
    driving = copy.deepcopy(driving_original)
    consumption = copy.deepcopy(consumption_original)
    leng=4
    first = 0

    for x in range(2189*4):
        B=np.arange(x*leng+first, (x+1)*leng+first)
        consumption[B,[np.argwhere(np.sum(driving[B, :],axis=0)==4)]] = energy[B,0]
        driving[B,[np.argwhere(np.sum(driving[B, :],axis=0)==4)]] = 11
    toc1=time.time()
    print("Power from FFR Process time: " + str(int(toc1-tic1)) + " s")
return consumption, driving

8.1.5 Include efficiency losses

def addEfficiency(consumption,eta):
    Ebat=np.where(consumption>0,consumption*eta,consumption/eta)
return Ebat

8.1.6 Charging control

def chargeControl(driving, consumption_original,regulationPower,chargerEfficiency):
    tic1=time.time()
    consumption=copy.deepcopy(consumption_original)
    correcingPower=(10-regulationPower)/4
    SOC=np.zeros((driving.shape[1]))

    for tid in range(len(driving)):
        Ebat=addEfficiency(consumption[tid-1,:],chargerEfficiency)
        SOC = np.add(SOC,Ebat)
        consumption[tid,np.logical_and((driving[tid,:]==10),(SOC>15))]=0
        consumption[tid,np.logical_and((driving[tid,:]==10),(SOC<-5))]=2.5
        consumption[tid,np.logical_and((driving[tid,:]==11),(SOC>10))]=correcingPower
consumption[tid, np.logical_and((driving[tid, :] == 11), (SOC < -10))] += correctingPower

toc1 = time.time()
print("Charge Control Process time: " + str(int(toc1 - tic1)) + " s")
return consumption

8.1.7 Charging cost

def costUserCharging(driving_original, charging, spotPrice, eta):
    tic1 = time.time()

    tripStartTime, tripStartEV, driving = calTripStart(driving_original)

    gridE_onlyDrive = calDriveConsumption(driving, tripStartTime, tripStartEV, eta)
    print(gridE_onlyDrive[:8, :8])

    gridE = userCharge(gridE_onlyDrive.copy(), charging, eta)
    cost = np.dot((gridE - gridE_onlyDrive).T, spotPrice)

    throughput = np.sum(np.absolute(addEfficiency(gridE, eta)), axis=0) / 1000

    soc = np.cumsum(addEfficiency(gridE, eta), axis=0, dtype=float)[:4]
    toc1 = time.time()

    print("User Charge scheduling Process time: " + str(int(toc1 - tic1)) + " s")
    return cost, throughput, soc, gridE, gridE_onlyDrive
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