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Intelligent Energy Management of Electric Vehicles in Distribution Systems

Short Master Thesis in Electric Power Systems and High Voltage Engineering

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SYNOPSIS:

In this short master thesis an optimal charging and discharging algorithm for Electric Vehicles and a later verification of the results in a distribution system are presented. A first algorithm without EVs is run to determine the ordinary cost and the normal loading conditions of the distribution system. The second algorithm includes the electric vehicles and minimises the total cost of the system attending to economic criteria. Both algorithms were programmed using GAMS software. Three different cases were created and three hourly prices from different days were used along the project for running all the simulations.
Optimal 24 hours charging and discharging plans are obtained respecting all the technical constraints from the EVs. These results are later validated in DIgSILENT PowerFactory using four different EVs distribution to check the technical constraints of the system.
An economic analysis is also performed to determine if the system cost is reduced by the intelligent management of the energy and the use of the V2G technology.

Alberto Palomar Lozano

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By signing this document, the author confirms that he has participated in the project work and thereby he is liable for the content of the report.

Preface

The following report represents the short Master Thesis project or 10th semester project entitled "Intelligent Energy Management of Electric Vehicles in Distribution Systems" written by the M.Sc. student Alberto Palomar Lozano at the Department of Energy Technology at Aalborg University. The report was conducted during the period from the 1st February 2012 until the 31st May 2012.

This project is a continuation of the 8th semester project "Intelligent Charging of Electric Vehicles in a Distribution Power System" written by Aleksandr Sleimovits, Kenneth Ronsig Kanstrup, Martin Handl and Alberto Palomar Lozano at Aalborg University. It is also using a DIgSILENT PowerFactory model built by Cam Pham and Martin Handl for the 9th semester course "Future Power Systems in Denmark" hosted by Energyminds in 2011.

The report is organised in chapters and sub chapters. Every chapter begins with an introduction where the objectives are defined. Figures, tables and equations are identified by their chapter number in A.B format, where A represents the chapter number and B the identification number. References are shown in the following format [X] and can be found at the end of the report in the bibliography section. Finally, appendixes are referenced from the main report and are included after the bibliography. The enclosed CD-ROM contains the written project in PDF format, the MATLAB script for generate data and plots, some of the references and the DIgSILENT PowerFactory model. Due to the term and condition, consumer data are confidential and are erased in the model.

Acknowledgements

First of all, I would like to acknowledge my supervisors Assistant Professor Jayakrishnan Radhakrishna Pillai and Assistant Professor Pukar Mahat for their valuable guidance, supervision and their interesting suggestions throughout the semester of this final thesis. I am indebted to them for their patience and support, which have been very important in completing this work.

I would also like to extend my sincere thanks to my old group members Aleksandr Sleimovits, Kenneth Ronsig Kanstrup and Martin Handl for their work during the 8^{th} semester project as well as to Cam Pham for co-creating the simulation model in DIgSILENT PowerFactory.

I extend my gratitude to “Aalborg DSO Forsynings virksomhederne i Aalborg” for providing the network data for the different study cases. I am also very grateful to all the employees in the Department of Energy Technology at Aalborg University.

Apart from the technical advice, I'd like to extend my heartfelt gratitude to my parents, my grandparents, my brother, my sister, my uncles, aunts, cousins, etc. and all my family for their inseparable support and constant love. If it wouldn't have been for them, nothing of all this would have been possible.

I also want to thank all the friends, colleagues, housemates, neighbours, etc. I have met during these two wonderful years in Denmark.

Last but not least, I would like to thank all my friends from school, from my home university (ICAI), from Santa Rita's Parish, etc. for all their encouragement and for being there through the good and especially the bad times.

Table of contents

List of Tables

List of Figures

I PROBLEM STATEMENT

1 Introduction

In this section, a short introduction for the Master Thesis entitled "Intelligent Energy Management of Electric Vehicles in Distribution Systems" is presented. Moreover, the reasons for choosing this project as well as its relevance are explained according to the final goals it is aimed to. Finally, a description of how it will be carried out is also included.

1.1 Introduction

The Electric Vehicles (EVs) represent a substantial change towards a less contaminant and a more environmentally friendly ways of transportation. The main idea is to have an alternative to the means of transport which are being used nowadays and are only based on fuels derived from petroleum. However, EVs have also pointed out in the last years as a solution to:

- Reduce CO2, NOx and other greenhouse gasses emissions.
- Cut down on the petroleum dependence, especially affecting to the high associated dependence from the exporting countries and the economic markets.
- Optimize the power system exploitation by flattening the demand curve.
- Integrate renewable energies into distribution system levels.
- Improve the energy efficiency in the transport sector.

On the other hand, the introduction of EVs into the different national distribution systems has been facing mainly two main disadvantages during the last years. The first problem is the big absence of charging points along with the lack of technology to establish and to control the charge and discharge of the connected EVs. The second one is the batteries deficient technology and performance as well as its price if compared to the traditional combustion motors.

Moreover, the vehicle-to-grid (V2G) technology, which allows the system operator to take some of the stored energy back to the grid, needs to be more developed and tested before becoming a reality.

Nevertheless, it is also important to remark important investments and research have been done recently in these fields obtaining quantitative progress and very promising results which will be described in the main report.

1.2 Motivation for the project

This project has been chosen due to the importance of the electric vehicle in an imminent short future.

The EVs are believed to be a key factor to revolutionize the distributions systems and the electricity markets. Because of this, the aggregation of EVs will be carefully and thoroughly analyzed as it is considered a great opportunity. However, it is necessary to admit it presents great risks as well.

A chaotic and non-programmed charge of EVs will bring the necessity to have a greater amount of power installed in the system. This means not only an unaffordable cost for some countries but also unnecessary. Those power peaks can be and should be avoided by an intelligent energy management. If the final aim is to have an efficient aggregation of electric vehicles, research in the intelligent management of EVs charging needs to be done. This is one of the main areas this project will focus on.

It is also true that the power generation capacity in Denmark exceeds the demand limits. This happens especially during the nights due to wind power. If this fact is linked to the power demand curve asimmetry, the Electric Vehicles are an incredible opportunity to take advantage of all this extra power for using it when needed. The main idea remains the same as pumping-storage water plants: producing power when prices are high or it is really needed and accumulating it in the cheapest possible way. As Denmark lacks of mountains and there is no hydropower plants using the pumping technology, all efforts must be placed in the promising EVs technology.

In addition to this, the Danish government promised to the European Union to have a 50% of renewable energy production in 2020, rather than 20% of most of the countries. This political compromise makes the analyses and introduction of energy storage technologies, such as the Electric Vehicles, into the power systems more urgent. In order to achieve this, further research must be done and motivational campaigns and some economical helps are planned to encourage people to purchase their own EV.

Summarising, due to the special characteristics of the Danish power system, where wind power plays a vital role for the energy generation, the interaction between any energy storage facility and power production must be studied and tested as soon as possible.

Although this project is not dealing directly with any generation source, it will be using real data from a Danish neighbourhood as well as real prices, which come up as the generation and the demand intersection in the spot energy market. For this reason, it can be stated that the proposed algorithms in this project will indirectly take advantage and maximise the benefits of the wind power in a Danish distribution system.

1.3 Goals

This project is intended to analyse the impacts of electric vehicles and vehicles-to-grid in the local distribution grids.

One of the main objectives is the formulation of intelligent charging and discharging control algorithms to integrate those vehicles into the distribution power systems. Moreover, the possibility of having the EVs and V2Gs to provide a reliable and a profitable solution for grid support functions in a deregulated electricity market will be also investigated.

After this, all the results will be tested and validated by DIgSILENT PowerFactory simulations in secondary distribution test networks, especially in wind dominated systems like the Danish power grid.

Summarising, the main objectives of this project are:

- The development of intelligent charging and discharging algorithms attending to economic criteria using specific software and programming languages, such as MATLAB and GAMS.
- The formulation of an optimisation routine to emulate economic operation of EVs aggregation.
- The study of steady state analysis of low voltage feeders integrated with EVs and other distribution system components to verify the results.
- To investigate the possibility of grid support functions from EVs and V2Gs.

2 Problem Analysis

In this section the European Strategic Energy Technology Plan, the most important concepts related to this project such as the the smart grids, the electric vehicles, the battery, the V2G concept as well as a brief explanation about the electricity price in Denmark will be presented.

2.1 Strategic Energy Technology Plan

Due to the worlwide climate change, most countries in the world are conducting low-carbon policies and investing on efficient energy technologies.

The European Union, where Denmark belongs to, is facing these challenges through a new policy. The main target of the so-called SET-Plan is the transformation of the whole power system, introducing major changes in the production, transportation and consumption of energy. In short, the core idea behind the European Strategic Energy Technology Plan (SET-Plan) is to make low-carbon technologies affordable and as much competitive as possible to introduce them in the different economic markets.

The SET-Plan establishes an energy technology policy for Europe. It is a strategic plan to accelerate the development and deployment of cost-effective low carbon technologies. The plan comprises measures relating to planning, implementation, resources and international cooperation in the field of energy technology [17].

The European Industrial Initiative on the electricity grid looks to develop, demonstrate and validate the technologies, system integration and processes to [17], [8]:

- Enable the transmission and distribution of up to 35% of electricity from dispersed and concentrated renewable sources by 2020 and make electricity production completely decarbonised by 2050.
- Further integrate national networks into a truly pan-European, marketbased network.
- Optimise the investments and operational costs involved in upgrading the European electricity networks to respond to the new challenges.
- Guarantee a high quality of electricity supply to all customers and engage them as active participants in energy efficiency.
- Anticipate new developments such as the electrification of transport.

However, the European policy is not only about the electricity grid objectives presented above. The SET-Plan also includes: The European Industrial Bioenergy Initiative, The European CO2 Capture, Transport and Storage Initiative, The European Electricity Grid Initiative, The Fuel Cells and Hydrogen Joint Technology Initiative, The Sustainable Nuclear Initiative, The Smart Cities Initiative, The

Solar Europe Initiative,The European Wind Initiative, The SET-Plan Steering Group (SET-Group), The European Energy Research Alliance (EERA) plus the SET-Plan Information System (SETIS) to manage them all [18].

One of the key factors to make this plan become a reality is the establishment of the Smart Grid, which will be introduced in the following section.

2.2 Smart Grids

In this section the Smart Grid will be presented along with some European Projects which are being carried out to develop it. One of the reasons for introducing this concept is the need for improving the data collection and analysis among others in the distribution systems.

For example, as it was previously described in section 1.2 on page 4, if the aims of this project are to develop an intelligent EVs charging plan and to investigate their grid support functions, real-time decisions must be taken depending on the grid status. Unless all data concerning technical issues can be collected, computed and carefully analyzed in a fast and efficient way, power systems will continue functioning as they do now. The upcoming Smart Grids are expected to provide these new features.

However, when trying to define this concept, not a single and unique definition for the Smart Grid can be found. For instance, the Smart Grid European Technology Platform defines a smart grid as an “electricity network that can intelligently integrate the actions of all the users connected to it - generators, consumers and those that do both, in order to efficiently deliver sustainable economic and secure electricity supply” [8].

The IEEE and the National Institute of Standards and Technology of the USA (NIST) present the Smart Grid conceptual framework shown in figure 2.1.
As it is depicted, there are seven important domains: Bulk Generation, Transmission, Distribution, Customers, Operations, Market and Service providers. It also shows all the communications and energy/electricity flows connecting each domain and how they are interrelated. Based on IEEE, the Smart Grid is seen as a large "System of Systems," where each NIST Smart Grid domain is expanded into three Smart Grid foundational layers: the Power and Energy Layer, the Communication Layer and the IT/Computer Layer. Second and third layer are enabling infrastructure platforms of the Power and Energy Layer that makes the grid "smarter" [19].

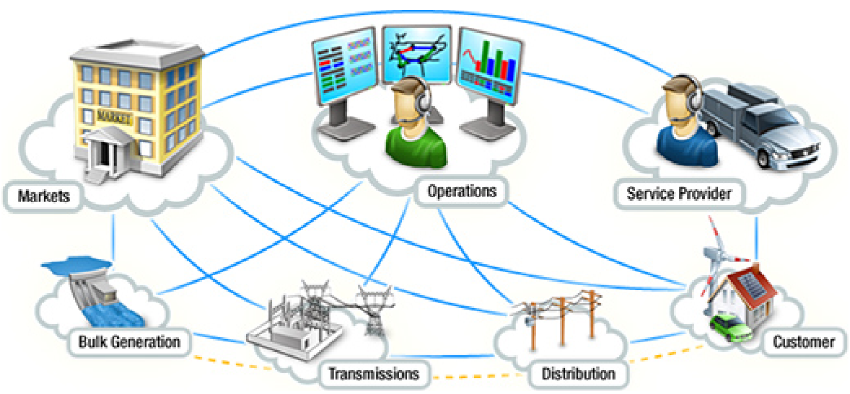

Figure 2.1: Smart Grid conceptual framework [3].

According to the SET-Plan described in section 2.1 on page 7, the European Electricity Grid Initiative (EEGI) has proposed an European research, development and demonstration programme. This programme was initially started by the electricity transmission and distribution network operators to accelerate the innovation and the development of the electricity networks of the future in Europe, in other words, the Smart Grid. The Smart Grid will be a usercentred, market-based, interactive, reliable, flexible, and sustainable electrical network system. Its deployment started by 2010 and it will be progressively devepoled until 2030, resulting in benefits such as [8]:

- Increased hosting capacity for renewable and distributed sources of electricity.
- The integration of national networks into an only market-based European network.
- A high level of quality of electricity supply to all customers.
- The active participation of users in markets and energy efficiency.
- The anticipation of new developments such as a progressive electrification of transport.
- An economically efficient deployment of future networks, for the benefit of grid users.
- The opening of business opportunities and markets for new players in the smart grids arena.

2.2.1 Some R & D European projects

Some of the most well-known European programmes and studies related to the research and implementation of SmartGrids being developed right now are listed here [20]:

1. PRIME: PoweRline Intelligent Metering Evolution.

   This alliance is focused on the development of a new open, public and non-proprietary telecom solution which will support not only smart metering functionalities but also the progress towards the Smart Grid. Power line communications is the most suitable and natural technology to provide the needed telecoms performance, even in complex underground electricity grids [21],[20].

2. OPEN meter: Open Public Extended Network Metering.

   The main objective of this project is to specify a comprehensive set of open and public standards for supporting electricity, gas, water and heat metering, based on the agreement of all the relevant stakeholders in this area, and taking into account the real conditions of the utility networks so as to allow for full implementation. The Scope of the project is to address knowledge gaps for the adoption of open-standards for smart multi-metering equipments. The resulting draft standards will be fed into the European and International standardization process. Morevoer, this project is strongly coordinated with the smart metering standardisation mandate given by the European Commission to the European Standardization Organizations [22],[20].

3. FENIX: Flexible Electricity Networks to Integrate the eXpected "energy evolution".

   The objective of FENIX is to boost the Distributed Energy Resources (DER) by maximizing their contribution to the electric power system, through aggregation into Large Scale Virtual Power Plants (LSVPP) and decentralized management. This program will increase the Distributed Energy Resources share in an economical and secure while keeping the security of supply given the high penetration of DER with low-flexibility generation (especially renewable energies). Summing up, this program is in charge for designing and demonstrating a technical architecture and commercial framework that would enable DER based systems to become the solution for the future cost efficient, secure and sustainable EU electricity supply system [23],[20].

4. ADDRESS - Active Distribution network with full integration of Demand and distributed energy RESourceS.

   ADDRESS is a large-scale Integrated Project founded by the European Commission under the 7th Framework Programme, in the Energy area for the "Development of Interactive Distribution Energy Networks". Its main target is to enable the Active Demand in the context of the smart grids of the future, or in other words, the active participation of small and commercial consumers in power system markets and provision of services to the different power system participants. Morevoer, ADDRESS is framed in the Smart Grids European Technology Platform [24],[20].

In a distribution system, a smart grid with smart metering has the potential for more efficient energy use and decentralized energy production on the level of small consumers. On this level, the consumption of electricity might increase significantly in the near future, as a result of in the introduction of electrical cars, electric heat pumps and possibly the absence of gas connection in some places [25]. In addition to this, the grid will need to be adapted to create the new possibility for reversing occasionally the currents. By allowing currents flowing back into the higher voltage grid, power will be supplied from the discharge of the connected EVs.

The smart grid promises a more efficient way of supplying and consuming energy. Essentially, the smart grid is a data communications network integrated with the power grid which collects and analyzes data about power transmission, distribution and consumption. Based on this data, smart grid technology then provides predictive information and recommendations to utilities, their suppliers, and their customers on how best to manage power [26].

This behaviour is exactly what is needed for the proper management of the future electric vehicles.

Neverthelss in order to reach this functionality from the grid, new equipment has to be implemented on every level of the power system. On a distribution level, not only Hybrid and Plug-in Electric Vehicles plus Vehicles-to-Grid technology, which will be described later, but also residential scale heat pumps, solar photovoltaic panels, small wind turbines and grid energy storage units to enable the bidirectional power flow.

In addition to all this, sensing and control devices such as smart meters, smart sockets, smart wires, power management units (PMU), power line sensor networks and phasor measurement units will play a major role. Finally, another key element will be the communication infrastructure based on fibre-optics, microwave, wireless and/or radio networks like GSM, CDMA. The task for this communication network will be to process huge amount of data assigning different priorities [19, 27, 28].

The possibility of an increased connectivity presents many benefits, including giving consumers greater ability to control their power consumption and their energy bills. The smart grid also gives distribution and transmission grid operators more visibility and control over power supply, source, quality, and costs [26].

Summarising, the Smart Grid has several phases of activities within the utility industry: from providing communications, monitoring and control capabilities for the energy infrastructure at the macro scale to controlling the energy usage of home appliances at the micro scale [29].

It is precisely this last feature that is explored in this project.

2.3 Electric Vehicle

An Electric Vehicle (EV) is any kind of vehicle which uses an electric motor for propulsion powered by rechargeable battery packs, ranging from cars, motorcycles, trains, trucks, etc. until boats, aeroplanes and even spacecrafts. However, these vehicles might be powered only by electricity or they may also have an internal combustion motor, becoming part of the hybrid technology.

This project will focus on normal electric cars, which consumers are expected to purchase in the upcoming years. These EVs are similar to the fossil fuel ones but they do not have any CO_2 or any other pollutant gas tail pipe emissions. As a direct consequence of this, electric vehicles can significantly help to reduce the pollution in cities.

Electric cars are expected to have a major impact on the vehicle industry given their role in reducing pollution as well as reducing dependence on oil [4].

Figure 2.2 shows the most important parts of an EV.

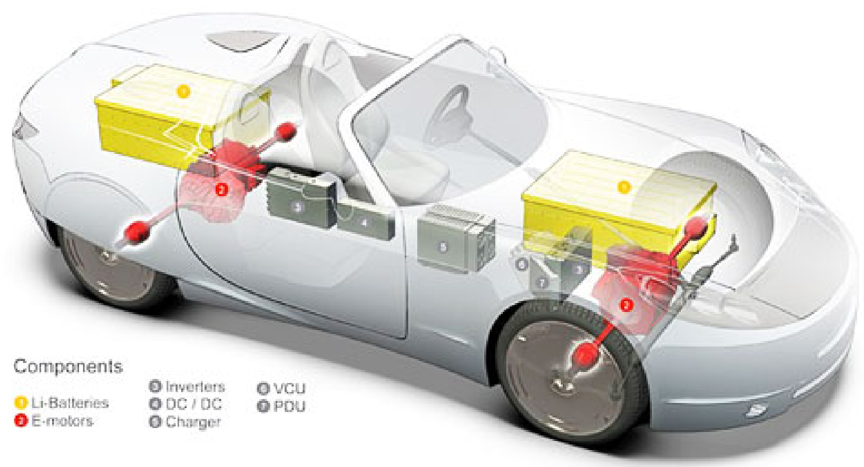

Figure 2.2: Typical components of an EV [4].

In a standard vehicle, three main parts can be diferentiated:

- Firstly, the most important part of an EV is the electric motor because it is responsible for the propelling the car. Right now there are three different types which can be found: the DC wound, the Permanent magnet DC and the AC motor. Although the AC is the most complex, it is also the most efficient one. On the other hand, the DC wound is the simplest to install but it produces less power. Depending on the type of motor, some vehicles might need more power electronics than others.
- Next element in order of importance for EVs is the battery. In a few words, energy is stored in the batteries and used whenever needed. More about batteries is described in section 2.5.

- Lastly, the third part is the controller. Generally speaking, this controller manages the power of the EV. It supplies to the motor with the precise amount of energy needed from the batteries. The controller is essential as it synchronizes the operation of both the motor and the battery through rectifiers, inverters and other devices.

As previously mentioned, the main reason why EVs are becoming so popular all over the world is the need to avoid dependence on the limited oil resources and reduce greenhouse gasses emissions. The leading consumer of oil activity and consequently the biggest source of carbon dioxide emissions into the atmosphere is the transport sector. Due to this fact, the electric vehicles are expected to be a suitable alternative to conventional fossil fuels transportation.

The leader in actually getting electric cars on the road seems to be Denmark [30]. With just a population of 5.5 millions, Denmark is the European leader in the Electric-Car Race. This country appears to be better prepared for the upcoming high penetration of EVs than any other European country.

One of the reasons which contributed to this leadership is that 85% of Denmark inhabitants live in urban areas [31]. This makes the danish scenario perfectly suitable for integrating electrical transportation. Moreover, the average driving distance in Denmark is 42.7 km per day [32]. This characteristic is also important for the EVs implementation because of the limited capacity of the battery.

Another reason which has lead Denmark to the top place is about taxes. Electric vehicles weighing less than 2.000 kg are exempt from the new car registration tax. However, this exemption does not apply to hybrid vehicles [33].

Finally, there is also an idea to make free parking zones for environmentally friendly transport [34]. According to Danish Energy Association, 400000 electric cars on the roads is the target for Denmark for the year 2020 [35].

2.3.1 Type of EVs

Nowadays, several types of Electric Vehicles can be found in the market according to the different installed technologies. Now their main characteristics will be explained.

2.3.1.1 Hybrid Electric Vehicle (HEV)

This technology combines a large energy storage, an internal combustion motor with a battery and an electric motor. Among its characteristics, it can be pinned out the Energy Recovery System, which allows the electric motor to recharge the battery without plugging it to the grid. This motor uses the energy stored in the battery for the start-up process and as a secondary help to the combustion motor when accelerating.

The behaviour of this kind of EV can be seen in figure 2.3.

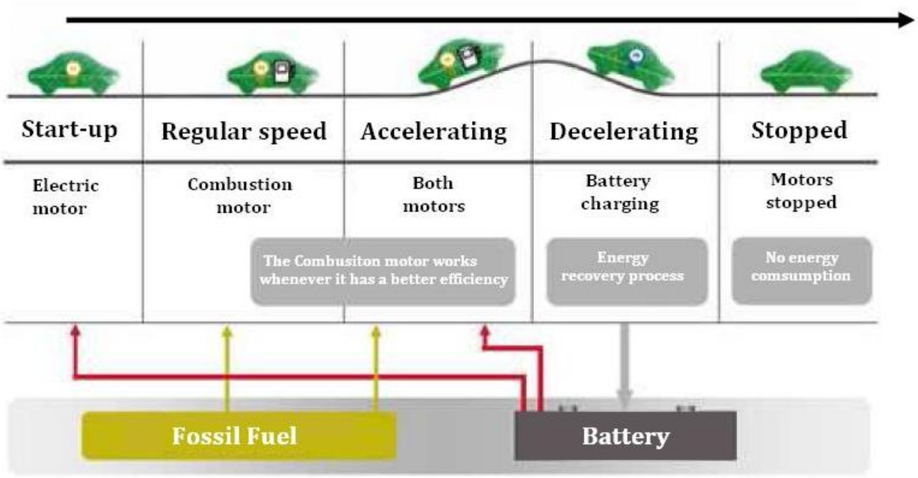

Figure 2.3: Hybrid EV normal behaviour.

Contemporary hybrid vehicles use the internal combustion engine whose shaft drives a generator so a small battery buffers the generator and absorbs the regenerative braking. After this, the battery and generator are able to power one or more electric motors that drive the wheels [7].

Some examples of this technology are the Toyota Prius or the Ford Escape Hybrid.

2.3.1.2 Plug-in Hybrid Electric Vehicle (PHEV)

The basic difference between PHEVs and HEVs is the possibility of recharging the battery by plugging it to the the grid or to any other external source.

Nevertheless, some other differences are listed here below [36]:

- Batteries for EVs need to be designed to optimise their energy storage capacity while batteries for PHEVs typically need to have higher power densities. These differences may lead to the development and use of different battery technologies for EVs and PHEVs.
- Batteries for PHEVs and EVs have different duty cycles. PHEV batteries are subject to deep discharge cycles and shallow cycles for power assist and regenerative braking when the engine is in hybrid mode while batteries for EVs are more likely to be subjected to repeated deep discharge cycles without many intermediate cycles. Current battery deep discharge durability will need to be significantly improved to handle the expected demands of EVs and PHEVs.
- When taking the vehicle range into account, PHEVs optimal battery capacity may vary by market and consumer group. On the other hand, minimum necessary range for EVs may vary significantly by region.
- In case of PHEVs, the electric range should be set to allow best price that matches the daily travel or allow individuals to set their own range. Moreover, EVs will perform differently in different situations such as weather, etc. and locations, therefore the operating costs may vary significantly.

Some examples of Plug-in Hybrid Electric Vehicles being manufactured now are the Chevrolet Volt or the Audi A5 e-tron.

Both hybrids EVs and PHEVs are being mass-produced nowadays but do not have the ability of supplying power back to the grid. This makes them impractical for V2G application [7] and not suitable for this project.

2.3.1.3 Battery EVs

These are the vehicles whose propulsion depends only and exclusively on an electric motor energised by a rechargeable battery. Because of this, sometimes they are also referred as "pure electric vehicles".

In figure 2.4 the operating schemes from a plug-in hybrid and a battery vehicle are compared. It can be seen how the plug-in EV configuration has an internal combustion motor powered by a fossil fuel plus an electric motor. This electric motor is connected to a battery, which can be recharged by plugging it to an external power source. On the other hand, the battery EV is only equipped with the electric configuration.

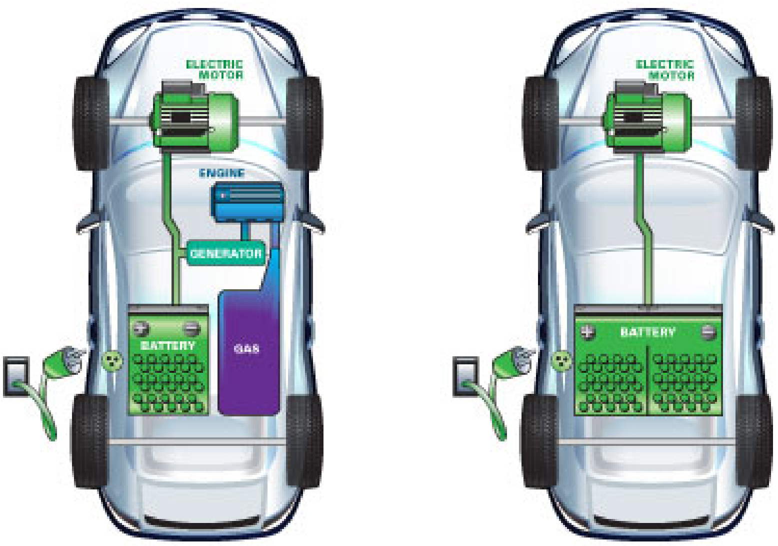

Figure 2.4: Hybrid EV (left) and Battery EV (right) diagrams [5].

This type of EVs stores the energy in the batteries in an electrochemical way. Before being used, they are plugged for a certain period of time to charge their batteries and later on they are unplugged to drive. Consequently, battery vehicles must have grid connection for charging, so the incremental costs to add the V2G technology are thought to be minimal. As it will be explained in the battery section, lead-acid batteries are currently the cheapest but nickel metal-hydride and lithium-ion are becoming more competitive due to longer cycle life, lower weight and smaller size [7].

Opel Ampera, Tesla Model S or BMW MINI E are some examples of this type of Electric Vehicle.

2.3.1.4 Fuel cell EVs

Last but not least, another type of EV needs to be presented: the fuel cell vehicle (FCV).

These vehicles run on hydrogen gas rather than any gasoline or fossil fuel and emit no harmful emissions to the atmosphere. FCVs usually store the energy in the hydrogen molecular form (H_2) and this material is fed into a fuel cell, where it reacts with the atmospheric oxygen. This reaction creates electricity and produces only water and heat as by-products.

However, most fuel cells designed for being used in vehicles produce less than 1.16 volts of electricity, which is very far from being enough to power a vehicle. Therefore, multiple cells must be assembled into a fuel cell stack. The final power generated by a fuel cell stack will depend on the number and size of the individual fuel cells mounted in the stack [6].

Figure 2.5 shows a look inside a typical fuel cell vehicle. The most obvious difference is the fuel cell stack that converts hydrogen gas stored onboard with oxygen from the air into electricity to drive the electric motor that propels the vehicle.

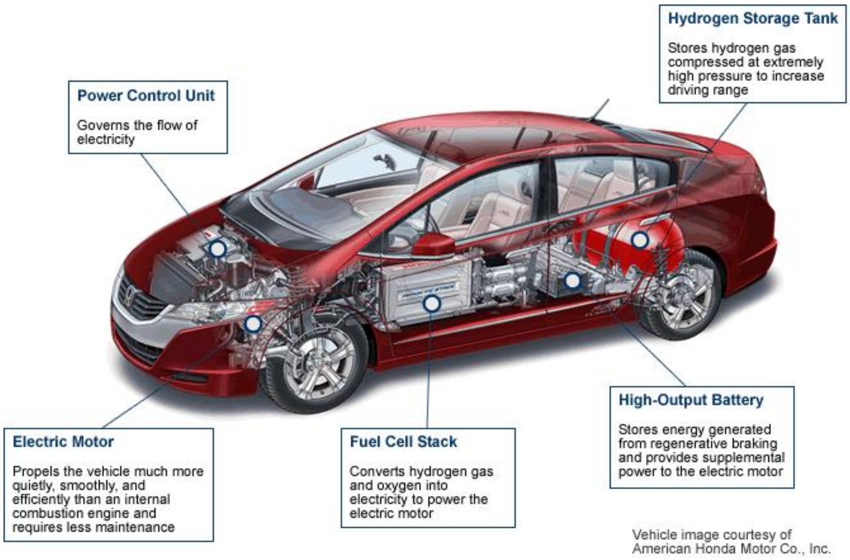

Figure 2.5: Fuel cell vehicle main components [6].

Nowadays, many different kinds of hydrogen storages are being developed such as binding the hydrogen to metals, pressurising H2 molecules in order to deal with bigger amounts of it or even producing it directly on-board from methanol, gasoline or some other fuels [7].

As a drawback, the FCV technology still needs to overcome some of this disadvantages [6]:

- Manufacturers must bring down production costs, especially for the fuel cell stack and the hydrogen storage, in order to compete with the other types of EVs or conventional cars. Fuel cell vehicles are currently more expensive than any other technology.
- The hydrogen storage capacity of FCVs has been proved to be enough to travel as far as gasoline vehicles under some circumstances, but this must be achievable across different models and without compromising customer expectations of space, performance, safety or cost.
- Fuel cell systems are not yet as durable as internal combustion engines, especially in some temperature and humidity ranges.
- The extensive system used to deliver gasoline from refineries to local filling stations cannot be used for hydrogen. New facilities and systems must be constructed for producing, transporting, and dispensing hydrogen to new consumers.

- Finally, fuel cell technology must be embraced by consumers and the market. By now it is normal consumers may have concerns about the dependability and safety of these vehicles, just as it happened with hybrids.

Although several challenges must be taken into consideration before FCV will be completely competitive, the potential benefits of this type of technology are substantial.

The fuel cell technology has already been implemented in some comercialized models such as the Honda FCX Clarity **??**, the Hyundai Tucson Fuel-Cell Electric Vehicle **??** or the Audi Q5 Hybrid Fuel Cell.

2.4 V2G concept

The basic concept of the Vehicle-to-Grid (V2G) technology consists on the possibility of the EVs to provide power back to the grid while being connected. It does not matter if this power comes from a battery, a fuel cell or a plug-in hybrid electric vehicle. The idea is basically to allow the electric vehicles not only to get power from the grid, but also to supply electricity back into it.

Although this technology is still being developed, in a short future it will allow the EV to discharge when needed or the EV owners decide. By doing this, some of the stored remaining energy in the batteries is fed again into the distribution system network. EVs batteries can be charged during low demand periods and discharge when more power is needed or some economic profit can be made.

This expected operating behaviour is very similar to the pumped-storage hydroelectricity, when during periods of high electrical demand stored water is released from a higher elevation reservoir to a lower elevation passing through turbines to produce electric power. Then throughout off-peak periods, low-cost electric power is used for pumping the water back again into the higher reservoir.

Many surveys among driving users show that an average vehicle is used for just one or a few hours within a day. It is precisely this fact which leads to the V2G concept. Theoretically, the batteries of the EVs could be used during the rest of the day by energy distribution companies as a storage media in case of high production and as a source in peak power demand periods. A new and different technology, but the same principle as the pumped hydroplants.

The Vehicle to Grid (V2G) concept is based on the energy storage in the electric vehicles but it is the price of the electricity which is the key factor for this concept. Whenever the energy consumption is low and the electricity price is accordingly cheap, EVs are expected to charge. When the demand gets higher and the price of the electricity rises, the energy stored in the batteries might be used both to support the electric grid functions or to earn some money.

In adittion, this technology can also help to buffer the constantly fluctuating balance of power in the power systems. Today the active power is produced and consumed simultaneously as there are no great storage facilities present in the power systems. This means that the supply must match the demand at every time. Otherwise, voltage rises and drops, overloading of some of the transmission lines, brownouts and even blackouts might occur [37].

Due to the behaviour of the final customers, constant fluctuations are always present in the grid. The vehicles with the ability of giving power back while connected can be used to match those small instantaneous variations of power rather than using any other generation source.

Furthermore, another feature from the V2G technology is the integration of intermittent renewable energies into the power systems. Thanks to these vehicles, the excess of power produced during periods of high wind or high solar irradiation will not be wasted but stored for a later use. It will also eliminate the need for building renewable energy plants with back-up fossil-fuel generators [38].

For a proper implementation of the V2G technology, each vehicle must have at least these three required elements: a connection to the grid for electrical energy flow, control or logical connection necessary for communication with the grid operator and controls and metering on-board the vehicle [37].

Figure 2.6 shows the conections between the electric vehicles with V2G technology and the electric power grid. Lines represent the power flow, so electricity flows from the generators to the end users through the transmission lines and the distribution system. Notice power also flows back from the connected EVs to the grid.

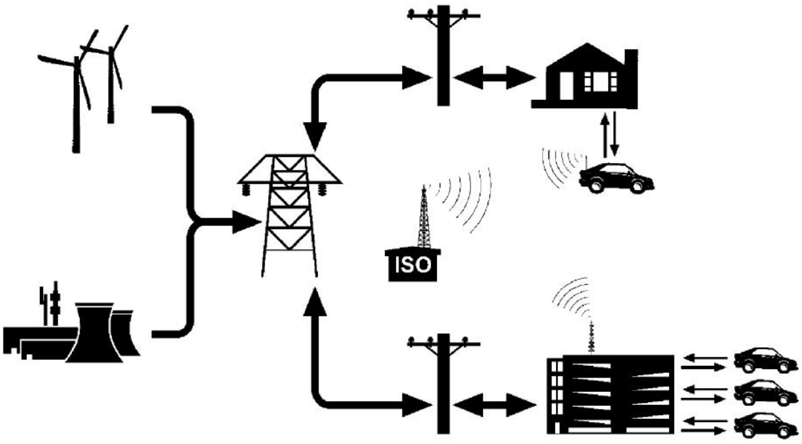

Figure 2.6: Power lines and wireless control connections between V2G and the grid [7].

The control signal from the grid operator, labeled ISO for Independent System Operator, sends a request for power to the vehicles. This signal may go directly to each individual EV, as depicted schematically in the upper right corner of figure 2.6, or to the main office of a fleet operator. This operator controls a larger amount of vehicles in a parking lot or through a third-party aggregator of dispersed individual vehicles as shown in the lower right corner of the same figure [7].

The second option just described is especially important regarding the V2G concept. One of the most important requirements for the V2G technology is that many electric vehicles are aggregated and managed together so they can have an impact into the grid. The maximum capacity of any typical EV technology battery is rather small and not enough to be noticeable at system distribution levels.

A standalone EV appears simply as noise in the power system at the grid level [39].

Finally, it is important to mention the implementation of the V2G technology in the system will definitely affect the electric vehicles impact into the distribution systems. This is one of the main issues to be analyzed in this project by simulating different study cases and scenarios.

2.4.1 V2G and the Smart Grid

After having presented these two concepts, it is clear the electric vehicles management will definitely need an established Smart Grid and the EVs will be a key part of it. The Smart Grid will provide the control needed to mitigate the load impacts and also to protect components of the distribution network from being overloaded by EVs thus ensuring electricity generating capacity is used most efficiently. With a Smart Grid, utilities can manage when and how EVs charging and discharging occurs.

In figure 2.7 another scheme about the Smart Grid divided by levels is shown. It can be seen how EVs will lay on the so-called level 3, connecting the final costumers to the distribution system. This is the reason why this project will be focused at a distribution system level in a local neighbourhood rather than including the generation and transmission parts of a power system.

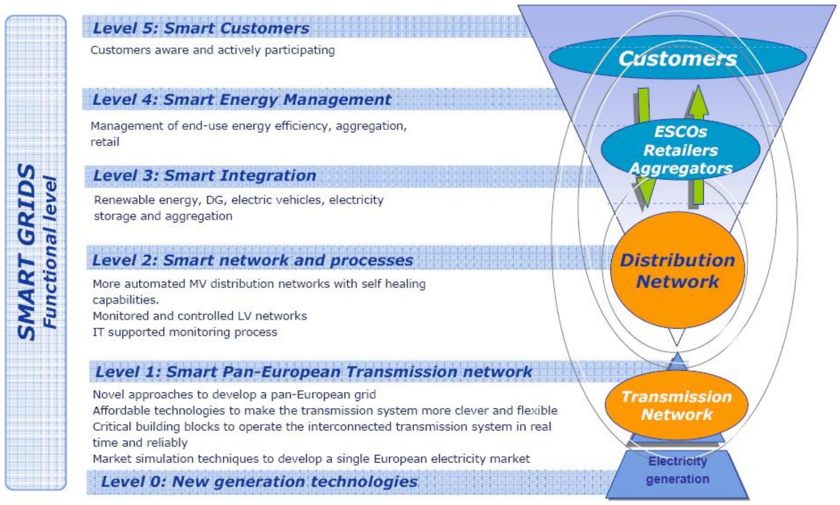

Figure 2.7: A possible Smart Grid model [8].

2.5 Battery

As a definition, it is generally accepted an electrical battery is a device composed by one or more electrochemical cells connected in series or parallel which can convert stored chemical energy into electrical energy through an electrochemical reaction.

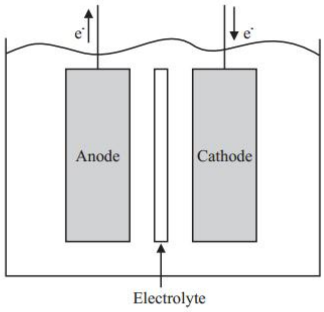

Figure 2.8: Scheme of an electrochemical cell [9].

In figure 2.8, it can be observed that an electrochemical cell consists of an anode, a cathode and the electrolyte, which separates the two electrodes. The principle of operation is as follows: during the discharge an oxidation reaction at the anode takes place. In this reaction a reductant (R_1) donates m electrons, which are released into the (connected) circuit, see equation 2.1. At the cathode a reduction reaction takes place. In this other reaction, n electrons are accepted by an oxidant (O_2), equation 2.2 [9]:

$$R_1 \rightarrow O_1 + m \cdot e^{-}, attheanode \tag{2.1}$$

$$O_2 + n \cdot e^{-} \rightarrow R_2, atthecatode \tag{2.2}$$

However, modeling the behavior of batteries is very complex because of non-linear effects during the discharge. In the ideal case, voltage stays constant during the discharge process, with an instantaneous drop to zero when the battery gets empty. The ideal capacity would be constant for all discharge currents, and all energy stored in the battery would be used. Unfortunately, in a real battery the voltage slowly drops during discharge and the effective capacity is lower for high discharge currents [40].

There are mainly two types of batteries:

- Primary batteries, also called disposable batteries as they are intended to be used once and discarded. The reason for this is that once the total amount of reactants is finished, these devices can not be energised again by any electrical manner.

  Nevertheless, these batteries have in general a higher energy density than rechargeable ones [41]. Common types of these batteries include zinc-carbon and alkaline batteries.

- Secondary batteries, which are designed to be recharged and used multiple times. These batteries can be restored to their original composition by applying electrical energy, which reverses the chemical reactions occuring during their usage.

  These type of batteries include dry cell types composed by nickel-cadmium (NiCd), nickel-zinc (NiZn), nickel metal hydride (NiMH) and lithium-ion (Li-ion) cells.

Regarding the connection to the EVs and this project, the vehicles use the energy stored in the battery for their propulsion. As it was described, there are many different battery types which can be used to equip the electric cars. There are three main types of batteries which are being used in electric vehicles nowadays: Lead-Acid, Nickel-Metal Hydride and Lithium-ion technologies.

Among these three different types, although there are no ideal contenders, the lithium-ion remains a good choice. The lithium-ion battery performance is constantly being improved as well as its technology of production. Also the costs of production are being reduced and lithium-ion batteries have the highest density of energy among all of the battery types.

Other advantages are that these batteries can charge quickly - up to 90% of their capacity in about 30-40 minutes. Moreover, the self-discharge rate is very low - up to a maximum of 5% per month. Finally, lithium-ion batteries are environmentally friendly [12].

Figure 2.10 shows the main tradeoffs of the five principal lithium-ion battery technologies in an outlook for 2020.

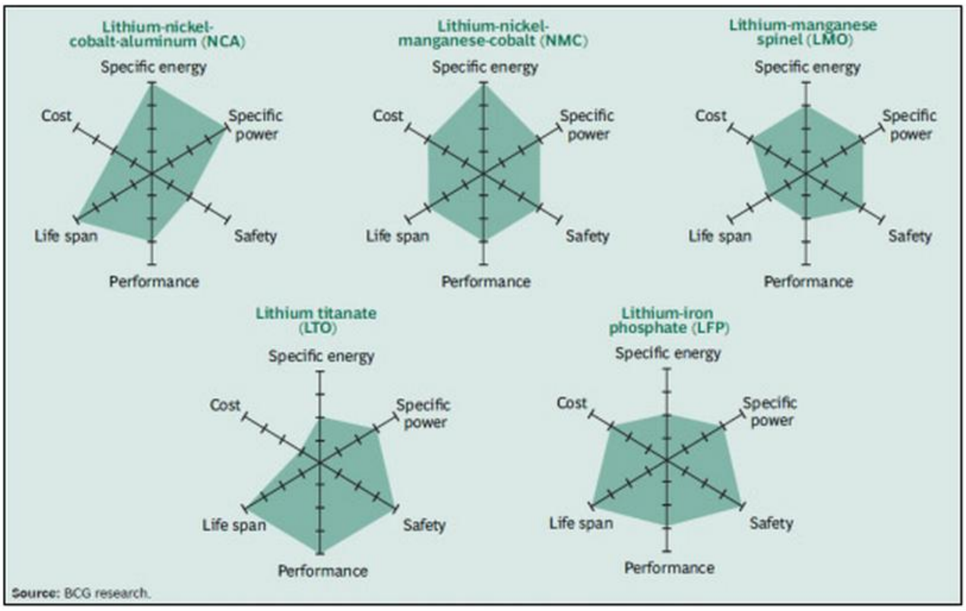

Figure 2.9: Tradeoffs among the five principal lithium-ion battery technologies [10].

It can be seen in figure 2.10 a battery comparation in terms of safety; specific energy, also known as capacity; specific power, or the ability to deliver high current on demand; performance, the ability to function at hot and cold temperatures; life span, which includes the number of cycles delivered as well as calendar life; and finally cost [10].

Now a brief summary explaining the most important characteristics of a battery shown above for the electric powertrain [42]:

1. Safety is one of the most important aspects when choosing a battery for the EV. The main concern is a thermal runaway of the battery. Carefully designed safety circuits with robust enclosures should virtually eliminate this, but the possibility of a serious accident exists. A battery must also be safe when exposed to misuse and advancing age.

2. Life Span reflects cycle count and longevity. Capacity loss through aging is a challenge, especially in hot climates. To compensate for capacity loss, EV manufacturers increase the size of the batteries to allow for some degradation within the guaranteed service life.

3. Performance reflects the condition of the battery when driving the EV in blistering summer heat and freezing temperatures. Unlike an IC engine that works over a large temperature range, batteries are sensitive to cold and heat and require some climate control. In vehicles powered solely by a battery, the energy to moderate the battery temperature comes from the battery.

4. Specific energy demonstrates how much energy a battery can hold in weight, which reflects the driving range. It is sobering to realize that in terms of output per weight, a battery generates only one percent the energy of fossil fuel.

5. Specific power demonstrates acceleration, and most EV batteries respond well. An electric motor with the same horsepower has a better torque ratio than an IC engine.

6. Cost presents a major drawback. The protection circuits for safety, the battery management for the status, the climate control for longevity and the 8 to 10 years warranty make this quantity bigger. Moreover, just the price of the battery itself amounts to the value of a vehicle with a combustion engine, essentially doubling the price of the EV.

However, after having explained the different parameters tested in figure 2.10, it can be concluded none of the five battery candidates show a significant advantage over the others, as the sizes of the shadowed spiderwebs are very similar in area, although different in shape.

2.5.1 Lithium-Ion Battery for the EVs

After having discussed about the different types of battery technologies, a brief explanation about the configuration and some of the technological parameters of the lithium-ion battery will be made.

As it was explained, this type of battery has many advantages over nickel-cadmium (NiCd) and nickel metal hydride (NiMH) technologies but also some restrictions due to its different principle of operation. Lithium-ion technology is used by EV manufacturers to create the most efficient batteries, which consists on single cells connected in series and parallel creating packs in order to perform the desired voltage.

The main elements of the lithium-ion battery shown in 2.10 are a positive electrode, a negative electrode and a chemical electrolyte in between them. This type of batteries use different chemical combinations of negative and positive electrodes but the same principle is applied.

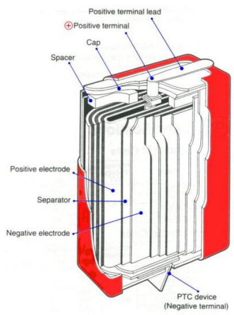

Figure 2.10: Lithium-ion cell of prismatic type [11].

The reaction mechanism of lithium-ion batteries is represented by figure 2.11. The positive and negative materials usually have several layers to make the lithium ions exchange easier. The effect of the charging and discharging reactions is the movement of lithium ions in between the electrodes. While the battery is charging, the lithium positive electrode gives up some of its lithium ions which move to the negative electrode through the electrolyte. When the battery is discharging, the lithium ions go back to the positive electrode. During this process, a corresponding flow of electrons in the external circuit appear, producing the energy to power the load.

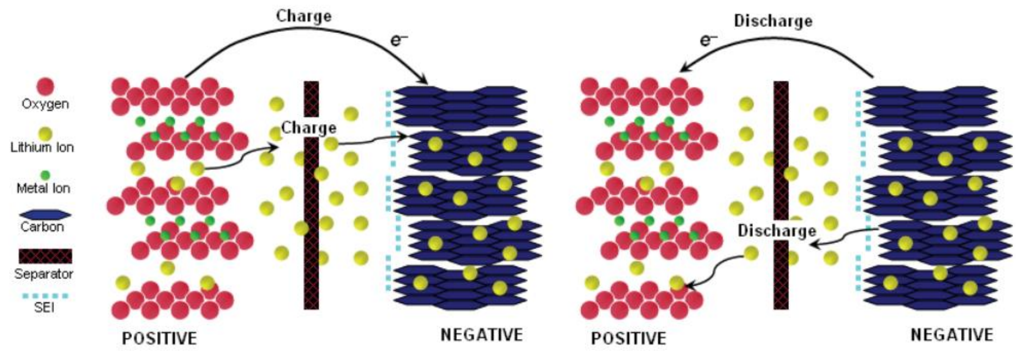

Figure 2.11: Representation of lithium-ion reaction mechanism [12].

Equations 2.3 and 2.4 describe in a chemical way the previously explained behaviour **??**.

$$CLi_x \rightarrow C + xLi^+ + xe^-, \tag{2.3}$$

$$Li_{1-x}CoO_2 + xLi^+ + xe^- \rightarrow LiCoO_2 \tag{2.4}$$

Although it is tempting to think of this process, called a "rocking-chair" mechanism, in purely physical terms the process is indeed electrochemical, being driven by the respective electrode voltages [12].

The use of lithiated cobalt oxide (LiCoO2) has remained the predominant positive material in the portable battery industry due to the high energy density and a cycle-life of around 500-700 deep discharge cycles [12].

Apart from life expectancy, one of the most important characteristics of the battery for this project is the charge capacity versus time curve. This feature can be seen in figure 2.12 for different charging rates.

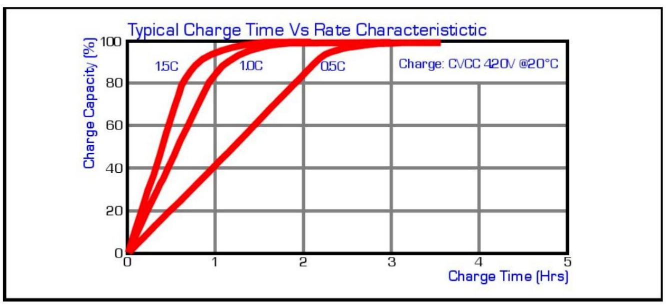

Figure 2.12: Lithium-ion rechargeable battery charging characteristics with different charging rates [11].

As it can be appreciated, the longer it takes for fully charging the battery, the more linear this charging curve becomes. Because of this, the charging and discharging characteristic will be assumed to be linear for this project. This assumption makes the model easier and will allow the algorithm to solve a linear programming problem.

All specifications for the battery model chosen for this project can be seen in section 4.3.2 on page 40.

2.6 Electricity Price

It is widely known the electrical consumption and the power supply in a power system must be always balanced. However, a noticeable amount of power could not be stored until now with the promising V2G technology. This is the reason why all consuption was being generated at the same time.

This feature has always made electricity trade special compared to any other sale of goods. According to this, power markets also have their own characteristics and among their functions are to balance the systems, to set the electricity prices, to regulate power exchanges, etc.

The Danish electricity market is an integral part of the Nordic electricity market, run by Nord Pool Spot which facilitates trade between producers and traders. Whenever electrical power balance between the consumption and the supply is ensured, the voltage frequency in the Nordic power system is 50.00 Hz.

The Nord Pool Spot (NPS) is an electricity exchange for Northern Europe, which consists of producers, traders, brokers and end users, as seen in figure 2.13.

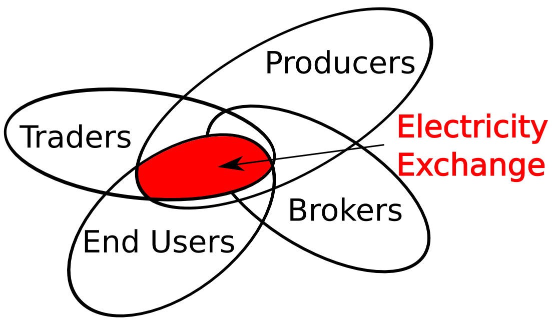

Figure 2.13: Schematic over the NPS electricity exchange and the players involved [13].

Market Participants are legal entities which operate in the wholesale and/or retail markets. They may play multiple roles but generally [43]:

- Producers normally operate both in the wholesale markets and power exchange markets, and contribute to levelling out any price differences between the markets. They also use the spot market to balance their generation schedules to delivery commitments close to time of operation.
- A retailer may ask the broker to find a producer who will sell a given amount of electricity at a given time [13]. Retailers normally serve end-users based on their own generation or power purchased in wholesale markets.

- End-users have various power volume requirements. Large-scale end-users may operate in the wholesale market, while retailers serve small-scale end-users.

- All participants act as traders in some sense as they trade in both physical and financial contracts to profit on price differences and volatility. For example, the trader may buy electricity from a producer and subsequently sell it to a retailer. The trader may also choose to buy electricity from one retailer and sell it to another retailer and so forth: there are many routes from the producer to the end user [13].

The NPS market is divided into several bidding areas, which can be seen in figure 2.14.

Figure 2.14: Map of bidding areas in the NPS market [14].

Elspot is Nord Pool Spot's day-ahead auction market, where electrical power is traded [13]. This means basically producers must offer a price for a certain power production the day before they produce it, and the buyers have to make a bid the day before they will use that amount of power. The NPS then calculates the price for every hour of the following day.

12:00 CET is the deadline for submitting bids for power which will be delivered the following day. Elspot feeds the information into a specialist computer system which calculates the price, based on an advanced algorithm [14].

As soon as the noon deadline for participants to submit bids has passed, all buy and sell orders are gathered into two curves for each power-delivery hour: an aggregate demand curve and an aggregate supply curve. The spot price for each hour is determined by the intersection of the aggregate supply and demand curves [43]. This can be graphically seen in figure 2.15.

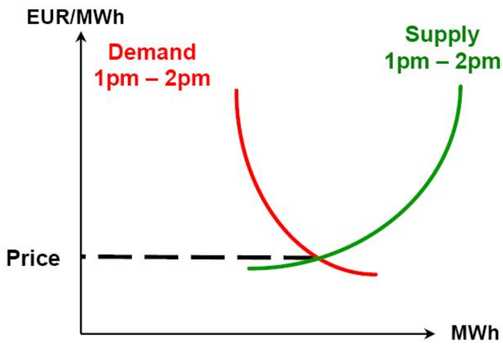

Figure 2.15: Demand curve and supply curve intersection for a certain hour [13].

This way of calculating the price is called a double auction, as both the buyers and the sellers have submitted orders [13].

Morevoer, the spot market is also the primary Nordic marketplace for handling potential grid congestion, the so-called bottlenecks such as insufficient transmission capacity in a sector of the grid, etc. In other words, Elspot is a market place where energy and capacity is combined in to one simultaneous auction [14].

In theory if there were no bottle necks, the price would be the same in all the areas described in figure 2.14. Despite the bottle necks the price will sometimes be the same in two neighbouring areas. In 2005, the price in all the areas was the same in 32% of the time [13, p.8]. One example can be seen in figure 2.16

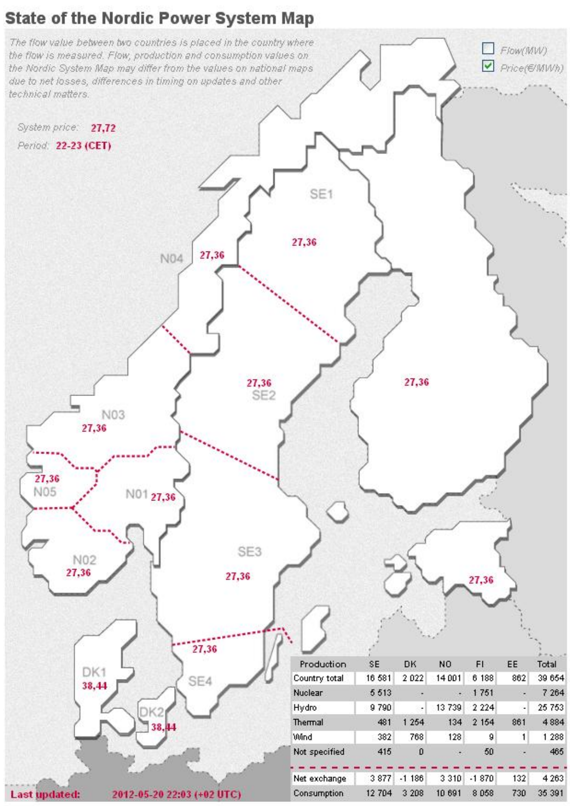

Figure 2.16: Different prices depending on the bidding area from the NPS market [15].

As it can be seen in figure 2.16, all different zones from Norway and Sweden plus Finland and Estonia have the same spot price at this precise hour. On the other hand, both East and West Denmark have a higher price. Note prices are in €/MWh.

Finally, figure 2.17 shows the prices during the whole day for a specific location on 22^{nd} September, 2011.

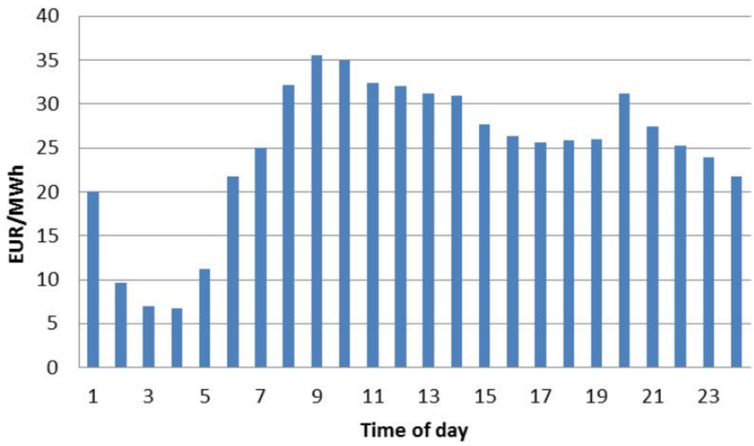

Figure 2.17: Hourly prices for September, 22^{nd} 2011 [13].

It is because of this Nord Pool Market that electricity prices are lower during the lowest power consumption hours and higher at the load peaks, as it can be checked by figure 2.17 and the daily load curve. This fact will make consumers more likely to charge their EVs when both consumption and price are low if possible.

However, the final price the consumers pay for the electricity in Denmark is a combination of the actual price with some fees and taxes [1]. These different fees and taxes can be seen in table 2.1.

Name	Charged by	Price [Øre/kWh]
Free electricity	AKE Supply A / S	48.10
Network service	AKE Net	15.40
PSO performance	AKE Net	7.50
Electricity duty	State Tax	69.00
Energy Saving Tax	State Tax	6.30
Distribution Contributions	State Tax	4.00
VAT	State Tax	37.58
Total price		187.88

Table 2.1: Electricity prices and taxes [1].

As it can be seen from table 2.1, the free electricity contribution to the final price is less than one fourth of the total. For this project, prices used for the simulations can be found in section 4.3.1 on page 39 and it will not take taxes into account.

II PROBLEM SOLVING

3 Distribution System

In this chapter the distribution system is presented and the optimization algortihms are introduced and explained.

3.1 System Description

The distribution network to be anaylized in this project is a residential area in the west part of Aalborg. A detailed map of the system can be seen in figure 3.1. All network data needed for simulation were provided by Aalborg DSO Company "AKE El-Net Forsynings virksomhederne i aalborg".

Figure 3.1: Distribution System area to be analyzed in Aalborg.

The equations in GAMS software for modelling the system as well as DIgSILENT PowerFactory components for validating the results will be carefully explained in the next chapter.

3.2 Problem Approach

When talking about the EVs charging and discharging opportunities, it has been interpreted as a mixed-integer linear programming problem for this project. The main reason leading to this is that an optimal solution subject to constraints needs to found by using mathematical tools, which is the basics of linear optimization. Typically these problems can be expressed in the following canonical form:

$$minimise \quad c^T x \tag{3.1}$$
$$subject\,to \quad A \cdot x \leq b \tag{3.2}$$
$$and \quad x \geq 0 \tag{3.3}$$

where c and b are vectors of known coefficients, A is also a matrix of known coefficients and $(-)^T$ refers to the transpose matrix operation.

However, due to the complexity electrical problems present, the final version of the algortihms look slightly different by adding more terms to the equations and different type of variables to the constraints. Moreover, in order to solve the problem in this way some assumptions needed to be made during the modelling of the system.

The model presented in this thesis is formulated as a mixed integer problem, including continous and binary variables as well as some of the most important technological and economic parameters and constraints.

As it was explained in the introduction, two different algorithms will be tested. The first one simply describes the distribution system without any electric vehicle, so it will just track the amount of power needed on an hourly basis to feed all the loads and obtaining the total cost. The results from this simulation will be used to compare and contrast the future results coming out from the addition of the EVs.

For the second algorithm, a whole model for the EV will be introduced into the system. In this extended version of the algorithm, an intelligent charging and discharging planning is obtained for the different EVs of the system attending to an economic criterion. The objective function of the algorithm will be minimising the total cost while respecting the technical constraints. After having run these new simulations and validated the results in DIgSILENT PowerFactory , tables and figures will be presented in the results chapter.

Finally, the economic differences between the two different systems will be also analyzed in the results chapter as a final conclusion for the V2G concept.

3.2.1 First algorithm explanation

The first algorithm refers to the distribution system without any EV. It only contains the hourly load data information to and the hourly prices in order to calculate the total amount of power needed and the total cost of it.

After running the simulation, this scenario will be validated in DIgSILENT PowerFactory to check the technical constraints refering to the overloading of cables and voltage changes.

Figure 3.2 shows the flowchart explaining the behaviour of this first basic algortihm.

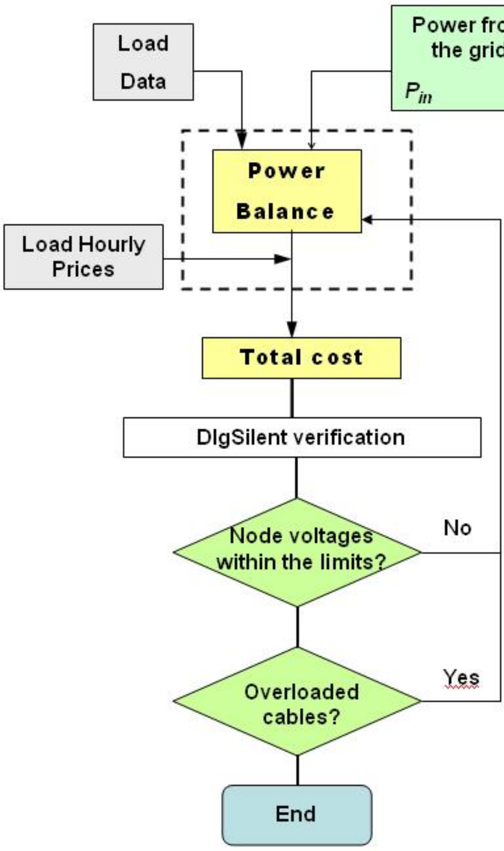

Figure 3.2: Flowchart of the first algorithm.

These results from this algorithm will be used as a reference for comparing and contrast the cost after having added the EVs and enabled the intelling discharging option with the V2G technology.

3.2.2 Including the EVs

For this new algorithm a maximum of 58 EVs will be added to the distribution system. Equations used for modelling it in GAMS software and the accurate parameters used will be described in the next chapter.

The main idea is to charge and if possible discharge the EVs in order to minimise the total cost of the system. This means to establish an intelligent charging and discharging plan so not so many power is needed from the grid. However, it is necessary to take into account more power will be needed than in the initial case for charging the vehicles.

Before running the algorithm, it can be predicted EVs will charge at the cheapest hours and will presumably discharge at the most expensive ones to save the highest amount of money. However, what can not be stated so easily is the amount of EVs able to charge and discharge at those times or if some EVs will need charging at different hours for different reasons. Moreover, it is also important to pay attention to the battery constraints, the connection and disconnection times, the state of charge of the batteries, etc.

Summarising, the main basis for charging and discharging the EVs in this algorithm is attending to an economic criterion but making sure all the loads are always supplied and the technical constraints from the EVs are respected. If these two things are achieved, some EVs might be able to give energy back to the grid at some times in order to re-use the power in the distribution system in an intelligent way.

After having run this algorithm, the technical constraints of the distribution system will be validated by simulating the results in DIgSIlent as in the previous case.

The flowchart for this complete algortihm can be seen in figure 3.3.

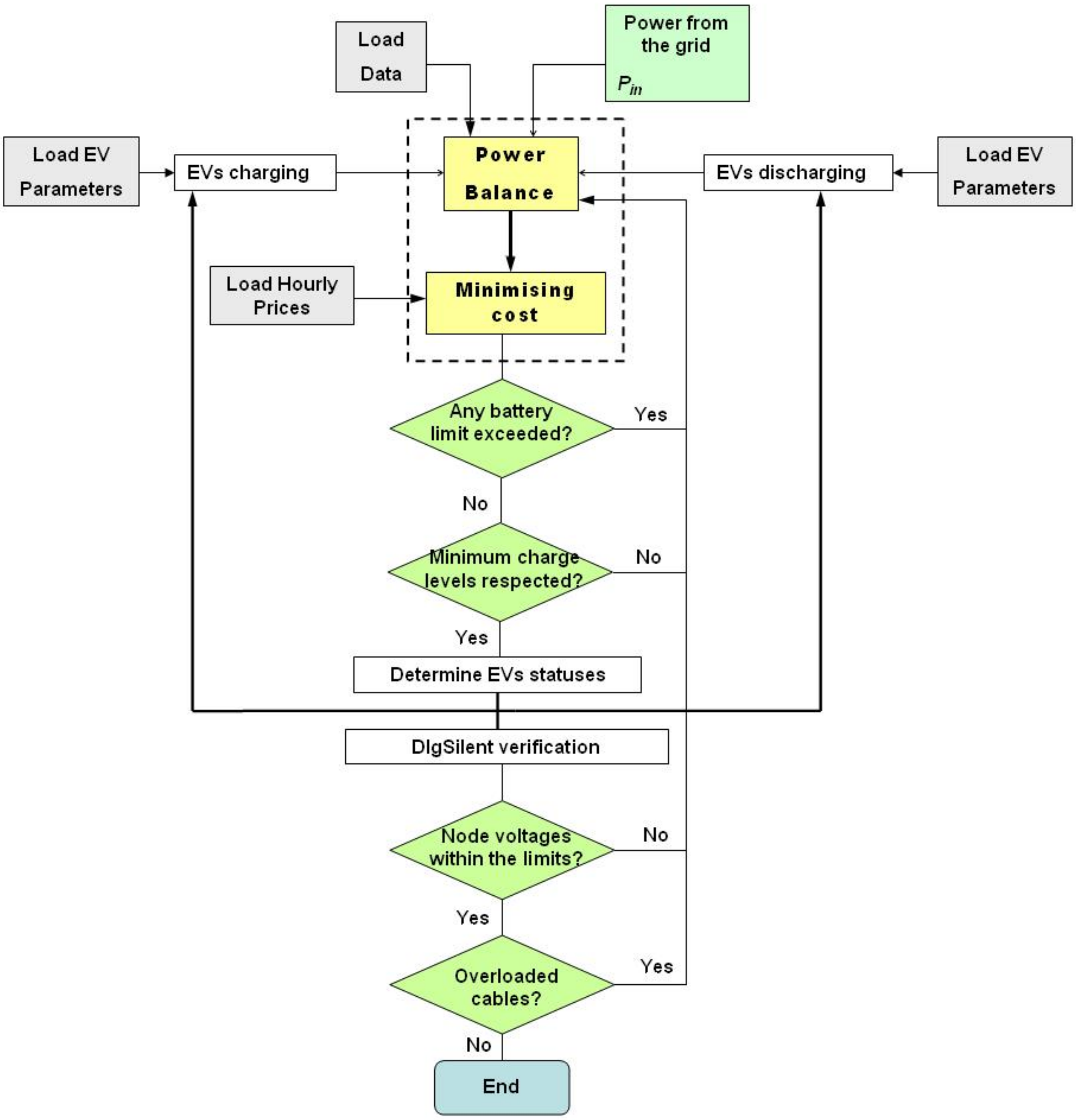

Figure 3.3: Flowchart for the second algorithm.

Note the dotted line represents the objective function of the optimisation problem of this project for minimising the toal cost of the system.

4 Algorithm Equations, Model Parameters and DIgSILENT PowerFactory Description

In this chapter the equations introduced for simulating the distribution system and the EVs will be and explained. Moreover, all The parameters needed for running the simulations are also defined and an explanation about the distribution system modelled in DIgSILENT PowerFactory for the validation of the results can be found.

4.1 Basic Model

First of all the distribution system model for the first algorithm is introduced. As it was explained in section 3.2.1 on page 30, the objective function is to minimise the cost but in this case there will be no EVs in the system.

4.1.1 Indeces, Parameters and Variables

In order to describe the Distribution System Model, the indeces, parameters and variables to be used are described in tables 4.1, 4.2 and 4.3.

Indeces	
p	Hours [h]
k	Grid nodes
m	Next Grid node

Table 4.1: Indeces for the Distribution grid Model

Parameters		
D_p	Demand for period p	kW
$price_p$	Power price in period p	cents €/kWh
$VMAX_k$	Maximum voltage in node k	pu
$VMIN_k$	Minimum voltage in node k	pu
$PMAX_{k,m}$	Maximum power through the line from node k to node m	kW
$PMIN_{k,m}$	Minimum power through the line from node k to node m	kW
V_B	Nominal Voltage	V
S_B	Base Power of the system	MW

Table 4.2: Parameters for the Distribution grid Model

Variables		
$P_{in,p}$	Power supplied into the grid in period p	kW
$P_{km,p}$	Power flow through the line from node k to node m in period p	kW
$V_{k,p}$	Voltage in node k in period p	pu
$V_{m,p}$	Voltage in node k in period m	pu
$cost$	Total cost of the system	€

Table 4.3: Variables for the Unit Commitment Model

4.1.2 Equations

In this section the equations associated to the problem will be presented including a brief explanation.

The first equation refers to the objective function of the problem. As it can be seen, equation 4.1 represents the cost of the distribution grid by multiplying the total power consumed by its respective hourly price, so the main goal will be to minimise it.

$$cost = \sum_{p} P_{in,p} \cdot price_p \tag{4.1}$$

Equation 4.2 expresses the active power balance for every period by matching the consumption to the power coming from the grid.

$$P_{in,p} = D_p \tag{4.2}$$

In the next section, an explanation about how this equation is affected by to the Evs introduced in the system will be presented.

Now all the equations associated to the technical constraints are listed.

Firstly, the power flowing through any distribution line must be within the limits.
This idea ideas leads to equations 4.3 and 4.4.

$$P_{km,p} \geq PMIN_{k,m} \qquad \forall p \tag{4.3}$$

$$P_{km,p} \leq PMAX_{k,m} \qquad \forall p \tag{4.4}$$

Although the lower limit might not be necessary in a real distribution system, it is needed to avoid strange results coming out from the algorithm while running the simulations.

The voltages in the nodes the same as the transmission lines are subjected to certain limits to be checked by the later DIgSilent validation. This can be seen in equations 4.5 and 4.6

$$V_{k,p} \geq VMIN_{k,p} = 0.9 \cdot V_B \qquad \forall p \tag{4.5}$$

$$V_{k,p} \leq VMAX_{k,p} = 1.05 \cdot V_B \qquad \forall p \tag{4.6}$$

where V_B represents the base voltage, set to 0,4 kV for the distribution system.

It is important to remark these four final equations were not finally introduced in the optimisation progress and will only be taken into account during the DIgSILENT PowerFactory simulations. So it is by running these other simulations when the technical constraints of the system are checked.

Finally, the GAMS software code for this algorithm can be found in appendix B.1 on page A7.

4.2 Modelling the EV

In this section, the whole model for the Electric Vehicle will be introduced in the system. This means new equations and constraints will be included in the distribution system model, affecting the existing demand and introducing the possible generation due to the V2G technology. All the results will be carefully analysed to asses the impact of those EVs.

As it was previously explained in section 2.4 on page 16, the Electric Vehicle is planned not to be just a passive consumer. Thanks to the V2G technology, these vehicles will be able to give some energy back into the grid if needed. In case of having a large amount of them following an intelligent charging and discharging plan, the cost of the system might be reduced. This is one of the possibilities to be investigated in this report.

According to the previously mentioned, the battery can be discharged because of two reasons once it is charged:

- For the normal use of the vehicle, driving in the roads.
- For generating some power back into the grid.

Now the description of the EV model will be exposed in an analogous manner to the previous section.

4.2.1 Indeces, Parameters and Variables

Firstly, all indexes, parameters and variables needed are listed in tables 4.4, 4.5, 4.6 and 4.7

Indeces	
c	EV fleet

Table 4.4: Index for the EV model

Parameters		
$MAXBAT_c$	Maximum energy in an EV battery	kWh
$MINBAT_c$	Minimum energy in an EV battery	kWh
$USE_{c,p}$	Binary condition to determine if the EV is being used (0) or connected to the grid (1)	{0,1}
$CONSUMPTION_c$	Average EV battery energy comsumption while running	kWh/km
$DISTANCE_c$	Average distance an EV runs per day	km/day
$MAXSOCGEN_c$	Maximum value of the function which limits if the battery can generate or not	%
$MINSOCGEN_c$	Minimum value of the function which limits if the battery can generate or not	%
$MAXSOCCHAR_c$	Maximum value of the function which limits if the battery can be recharged or not	%
$MINSOCCHAR_c$	Minimum value of the function which limits if the battery can be recharged or not	%
$RATE_c$	Charging/discharging rate to establish the amount of time needed to charge/discharge the battery	1/h
$\eta_{charge,c}$	Battery charginng/discharging process efficiency	%
$\eta_{transport,c}$	EVs mechanical efficiency	%
$MINCHARGE_c$	Minimum battery level for fleet c to be charged when an EV is going to be used	%

Table 4.5: Parameters for the EV Model

Variables		
$charge_{c,p}$	Amount of power charged into the EVs batteries from the grid in period p	kW
$generate_{c,p}$	Amount of power injected back into the grid from the EVs batteries in period p	kW
$energy_{c,p}$	Remaining energy in the EV batteries at the end of period p	kWh

Table 4.6: Variables for the EV Model

Binary Variables	
$gen_{c,p}$	Variable to determine if the EV battery can generate power into the grid (0) or not (1) in period p
$car_{c,p}$	Variable to determine if the EV battery can be charged from the grid (0) or not (1) in period p
$cond_{c,p}$	Variable to determine if an EV is generating (1) or charging (0)in period p

Table 4.7: Binary Variables for the EV Model

4.2.2 Equations associated to the EV Model

In addition to the equations presented for the previous network, in this section new ones will be added in order to model the EVs behaviour in a distribution system.

First of all, now equation 4.1 becomes equation 4.7 because of the possibility of discharging the electric vehicles when needed.

$$cost = \sum_{p} (P_{in,p} \cdot price_p - \sum_{c} generate_{c,p} \cdot price_p) \tag{4.7}$$

However, it is important to highlight how the power balance equation 4.2 gets modified when taking the EVs charging effect into account. This new formulation can be seen in 4.8.

$$P_{in,p} = D_p + \sum_{c} charge_{c,p} \tag{4.8}$$

The rest of the equations for modelling the distrution system will remain the same and the new ones will be added to them.

Now, the first step is to distinguish when the EV is being used and therefore consuming power according to the distance or when the EV is not running and connected to the grid. This condition will be defined by the use of the binary parameter $USO_{c,p}$. Moreover, in the last case, the EV might be charging the battery or giving back some power to the grid, so a further difference will need to be made.

Some other parameters to be present are the efficiencies of the different processes. When the battery is providing energy to the wheels through the motor, it is necessary to quantify the losses. As a whole, the energy coming out from the battery will have to be greater than the energy needed to move the vehicle. Because of this reason, the EVS mechanical efficiency will appear in the denominator of equation 4.9.

It happens exactly the same with the battery discharging process, so the same mathematical reasoning applies here. When the EV generates energy, electric losses will appear on the way back to the grid.

On the other hand, the energy stored in the battery when charging will be smaller than the energy coming out from the grid. That is the reason why the charging process efficiency is a multiplying factor in equation 4.9.

Summarising, this is the equation which expresses how the energy in the battery varies from one period to other.

$$\begin{aligned} energy_{c,p} - energy_{c,p-1} = [(USE_{c,p}) \cdot (\frac{genera_{c,p}}{\eta_{charge,c}} - charge_{c,p} \cdot \eta_{charge,c})] - \\ - (USE_{c,p} - 1) \cdot (\frac{CONSUMPTION_c \cdot DISTANCE_c}{\eta_{transport,c}}) \end{aligned} \tag{4.9}$$

For technical reasons, the energy stored in the battery has upper and lower limits. This can be seen in equations 4.10 and 4.11.

$$energy_{c,p} \leq MAXBAT_c \tag{4.10}$$

$$energy_{c,p} \geq MINBAT_c \tag{4.11}$$

However, it can be taken for granted that if the EV user wants to use the vehicle, it should have at least a minimum charge level not to run out of energy while driving. This way the typical driving patterns are always guaranteed. When an EV is planned to be used, the constraint about the minimum battery level for its usage described in equation 4.12 will apply. This equation will avoid batteries running completely out of energy while connected to the grid.

$$energy_{c,p} \geq MINCHARGE_c \cdot MAXBAT_c \tag{4.12}$$

Equations 4.13 and 4.14 model the condition needed for the battery not to give more energy back to the grid when the SOC is lower or equal to the predefined value known as $MINSOCGEN_c$ despite being still connected. This will be achieved through the binary variable $gen_{c,p}$.

$$\frac{energy_{c,p}}{MAXBAT_c} + MINSOCGEN_c \geq gen_{c,p} \cdot MINSOCGEN_c \tag{4.13}$$

$$\frac{energy_{c,p}}{MAXBAT_c} + MINSOCGEN_c + \varepsilon \leq (1 - gen_{c,p}) \cdot (MAXSOCGEN_c + \varepsilon) \tag{4.14}$$

Similarly, equations 4.15 and 4.16 model the constraints for the battery not to charge more than established maximum of $MAXSOCCHAR_c$ although the vehicle keeps also connected to the grid. In this case, this characteristic will be controlled through the variable $car_{c,p}$.

$$\frac{energy_{c,p}}{MAXBAT_c} + MINSOCCHAR_c \leq car_{c,p} \cdot MAXSOCCHAR_c \tag{4.15}$$

$$\frac{energy_{c,p}}{MAXBAT_c} + MINSOCCHAR_c - \varepsilon \geq (1 - car_{c,p}) \cdot (MINSOCCHAR_c - \varepsilon) \tag{4.16}$$

It can be appreciated how an infinitesimal value epsilon appeared in equations 4.14 and 4.16. This new value has been introduced in order to properly model the ”strictly less than” or ”greater than” inequalities as the software solver automatically assumes “less than or equal to” and “greater than or equal to” conditions.

Finally, the last technological point to be modelled is the battery charging and discharging capacity. By adding equations 4.17 and 4.18, the charging and discharging capacities are limited for every period p. In this way the amount of time batteries need to charge/discharge depends on the predefined $RATE_c$. Moreover, these two equations will be also used for relating the variables controlling the minimum SOC and the battery maximum to the variable $cond_{c,p}$, which will determine if the EV is charging or generating.

$$generate_{c,p} \leq (USE_{c,p}) \cdot (1 - gen_{c,p}) \cdot \frac{MAXBAT_c}{RATE_c} \cdot cond_{c,p} \tag{4.17}$$

$$charge_{c,p} \leq (USE_{c,p}) \cdot (1 - gen_{c,p}) \cdot \frac{MAXBAT_c}{RATE_c} \cdot (1 - cond_{c,p}) \tag{4.18}$$

4.3 Model Parameters

In this section all parameters needed for running the optimization algorithm implemented for this project will be explained. In addition to this, the different scenarios and cases studied will be also introduced.

4.3.1 First Algorithm

The parameters described for the first algorithmin in section 4.1 on page 33 are listed here except D_p, the demand for every period p, since load data must remain secret due to privacy terms.

Table 4.8 summarises the technical parameters needed for running the algorithm without EVs in the system.

Parameter Name	Value
$VMAX_k$	1.05 pu
$VMIN_k$	0.9 pu
$PMAX_{k,m}$	*
$PMIN_{k,m}$	*
V_B	0.4 kV
S_B	400 kVA

Table 4.8: Technical parameters from the distribution system.

- Symbol '*' means the parameter depends on the DIgSILENT PowerFactory simulations.

Table 4.9 shows the hourly electricity prices on an average spring day. It is an example of parameter $price_p$. All tables containing the hourly prices for the three different days analyzed in this project can be found in D on page A26 and they will be also used for the second algorithm.

Moreover, as a part of the economic analysis a constant parameter $price'$ is defined for running more simulation cases. This new parameter will be used for an economic comparison between paying accordingly to the different hourly prices and the possibility of paying a fixed price to the EVs giving energy back to the grid. For this project, the statistical mean price has been considered as a good starting point for this fixed-price, so equation 4.19 shows how $price'_p$ it is calculated.

$$price' = \sum_p \frac{price_p}{24} \tag{4.19}$$

Nevertheless, this is just a first approach to this idea. Deeper studies and simulations should be carried out to determine if energy coming from EV batteries should be paid according to market prices or at a higher set price by receiving subsidies, bonuses or any other kind of help to encourage people about V2G technology.

The only change to be introduced in the model about this new parameter is in equation **??**, turning into equation **??**

$$cost = \sum_p (P_{in,p} \cdot price_p - \sum_c generate_{c,p} \cdot price'_p) \tag{4.20}$$

Hour	Electricity Price (cents €/MWh)
1	0,7653
2	0,7631
3	0,7564
4	0,7428
5	0,7445
6	0,7404
7	0,7643
8	0,9096
9	0,9307
10	1,0037
11	1,0509
12	1,0032
13	0,8737
14	0,8330
15	0,8426
16	0,8555
17	0,8642
18	0,9001
19	0,8474
20	0,9468
21	1,0028
22	1,0028
23	0,9379
24	0,7655

Table 4.9: Hourly electricity prices for 21/04/2012 in West Denmark [2].

4.3.2 Electric Vehicle Parameters

About the parameters of the EV, it is important to stablish the difference about an EV battery charging or giving energy back to the grid. This fact will depend on their state-of-charge (s.o.c.)at every period p. According to [16], batteries release energy more easily when their s.o.c. is high or more exactly above a tolerance level. A level of 60% is stipulated to be the tolerance level for this project.

This means when the s.o.c. is lower than 60%, the battery will be only charging in order to avoid a decrease in the storage capacity within time. For the same reason, it is not convenient the battery continues charging when the s.o.c. gets percentages around 85% or 90%. For this project, 85% has been chosen as the limit to stop charging the batteries. These limits are illustrated in figure 4.1 where C is the storage capability.

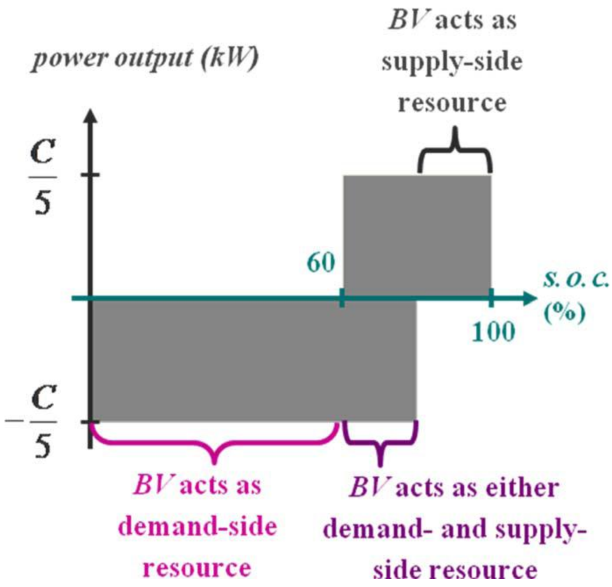

Figure 4.1: Functioning of the battery according to the energy stored [16].

By doing this, the battery performance is optimized and the degradation is reduced, resulting a longer battery life. However, the presented limits are not completely defined and the width of this band is still a topic of research [16].

For this project the minimum battery level to be charged when an EV is going to be used has been set to a 20% as a matter of security. Moreover, the average driving distance in Denmark is 42.7 km per day [32]. Others technical parameters from the BMW MINI E battery and motor such as the consumption, the charging and discharging rate while running and the efficiencies are described here [44].

Table 4.10 includes all parameters needed for the EV model.

Parameter Name	Value
$MAXBAT_c$	35 kWh
$MINBAT_c$	0%
$CONSUMPTION_c$	0.14 kWh/km
$DISTANCE_c$	42,7 km
$MAXSOCGEN_c$	100%
$MINSOCGEN_c$	60%
$MAXSOCCHAR_c$	85%
$MINSOCCHAR_c$	0%
$RATE_c$	3 h^{-1}
$\eta_{charge,c}$	93%
$\eta_{transport,c}$	86,5%
$MINCHARGE_c$	20%

Table 4.10: Technical parameters for the EV model.

4.3.2.1 Connection/Disconnection for the EVs

Finally, parameter $USE_{c,p}$ needs to be explicated before being introduced into the optimization algorithm.

It was explained when defining the EV model, the condition of having a vehicle connected to the distribution system or not would be controlled by this parameter. Therefore, five different user profiles have been used in order to create the connection and disconnection times for all the 58 EVs along the day. These profiles are the same which were used for the 8^{th} Semester project [38]:

User 1 is named "Normal worker". In this profile the vehicle is available for charging from 16:00 till 6:00.

User 2 is named "12 hour shift worker". The vehicle will be connected to the grid and available for charging from 18:00 till 4:00.

User 3 is named "Mother with children". The user leaves at 6:00 and comes back at 10:00 for leaving again at 14:00 and returning at 15:00. Then the user leaves at 17:00 to finally get back at 18:00.

User 4 "Two periods worker". This user is leaving the house at 7:00 and gets back at 12:00. After this, he is leaving again to work from 14:00 to 19:00.

User 5 is "Nigh shift worker". The car is being used between 22:00 and 8:00 and 17:00 and 19:00.

It is important to remark these user profiles have been generated for simplicity as no actual data for connection and disconnection are available.

Figure 4.2 shows graphically the different connection and disconnection times of the five profiles recently described.

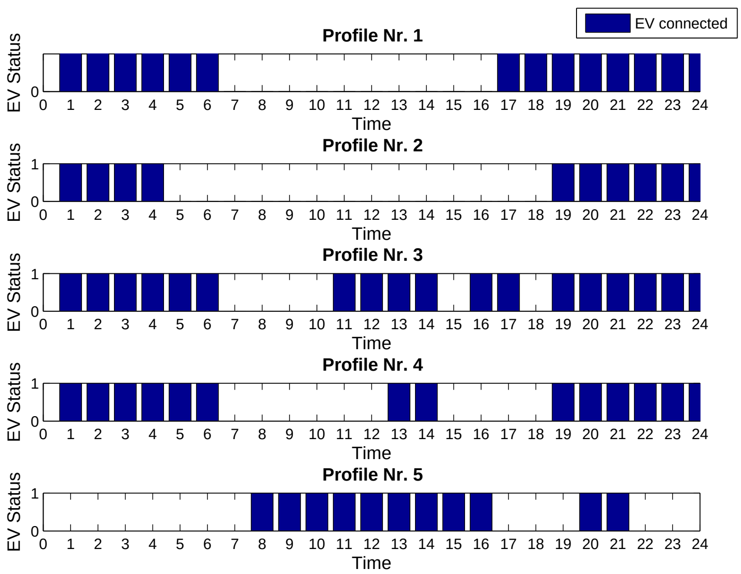

Figure 4.2: 5 different user profiles for having different connection and disconnection times.

In table 4.11 the different probabilities assigned to every profile are shown.

Type of profile	Probability
Nr. 1	60 %
Nr. 2	10 %
Nr. 3	20 %
Nr. 4	10 %
Nr. 5	Initially not connected

Table 4.11: Probabilities associated to every user profile.

Now the user profiles and their probabilities have been set, next step will be how to distribute the initial amount of EVs in the system. In order to generate the initial amount of EVs connected to the grid a normal distribution function was used. This statistical distribution depends on two parameters and has this probability density function:

$$f(x) = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{1}{2} \cdot \left(\frac{x-\mu}{\sigma}\right)^2} \qquad \text{for} -\infty < x < \infty \tag{4.21}$$

Where μ is the location parameter of the distribution known as the mean and σ is the standard deviation, containing information about the width of the distribution.

For this project, logical values of these parameters were programmed as it is very likely to have most of the electric vehicles connected to the power system by night. According to this, values for future simulations are expressed like:

$$\mu = 0.9 \cdot EV = 0.9 \cdot 58 = 52.2 \tag{4.22}$$

$$\sigma = \frac{EV}{10} = \frac{58}{10} = 5.8 \tag{4.23}$$

Where:

EV : Maximum number of connected EVs = 58

Once the initial amount of EVs connected is generated, this number is checked to prove it lays within the limits set for the project. In case of being greater than the maximum of 58 or lower than 20, number considered as the limit to make this algorithm not representative enough, this number is created again.

After having generated the initial connected EVs, the resulting number is rounded to the nearest integer and this amount of electric vehicles is randomly distributed all along the 58 positions of the distribution system.

The next step is loading the different user profiles described in section 4.3.2.1 on page 41 depending on the initial state (connected or disconnected) of every EV and according to the probabilities of table 4.11 to create the input parameter $USE_{c,p}$.

This process is described in the flowchart of figure 4.3.

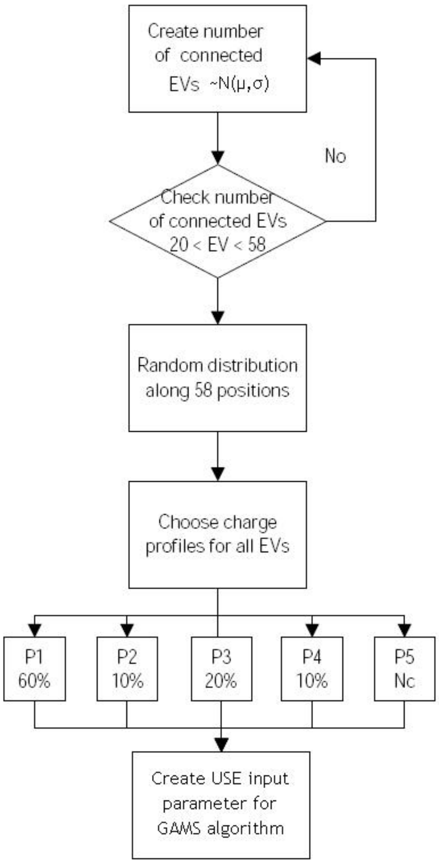

Figure 4.3: Flowchart of the initial scripts.

An example of parameter $USE_{c,p}$ as a result of having run all these steps can be seen in table 4.12.

EV & Hour	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1	1	1	1
2	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1	1	1	1
8	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	1	1	0	1	1	1	1	1	1
12	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	1	1	0	1	1	1	1	1	1
14	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
18	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
19	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
22	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
23	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
24	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	1	1	0	1	1	1	1	1	1
25	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
26	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
27	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
28	1	1	1	1	1	1	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1	1	1	1
29	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	1	1	0	1	1	1	1	1	1
31	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
32	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
33	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	1	1	0	1	1	1	1	1	1
34	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	1	1	0	1	1	1	1	1	1
35	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
36	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	1	1	0	1	1	1	1	1	1
37	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	1	1	0	1	1	1	1	1	1
38	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
39	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
40	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
41	1	1	1	1	1	1	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1	1	1	1
42	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	1	1	0	1	1	1	1	1	1
43	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
44	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	1	1	0	1	1	1	1	1	1
45	1	1	1	1	1	1	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1	1	1	1
46	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
47	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
48	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
49	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
51	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
52	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
53	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
54	1	1	1	1	1	1	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1	1	1	1
55	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
56	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
57	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
58	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1

Table 4.12: Example of parameter $USE_{c,p}$ input for the optimization algorithm for random case nr. 1.

4.3.2.2 EVs distribution examples along the day

In order to get some different EV distributions and to know where and when the EVs will be connected, three random setups different to the previous ones from the 8^{th} semester project are created. This is done by running the same code which is included in the MATLAB® files `Initial_EVs.m`, `Distribute_EVs.m` and `Load_Profile.m`. These files can be seen in appendix C on page A20.

Figures 4.4, 4.5 and 4.6 are the result of running these files three different times. They show the distribution of EVs available for charging along the day based on the presented user profiles for 58 EVs in the system. The three figures show the whole amount of available EVs for each of the 3 random setups. The specific location of each EV in the three setups can be seen in appendix **??** on page ??.

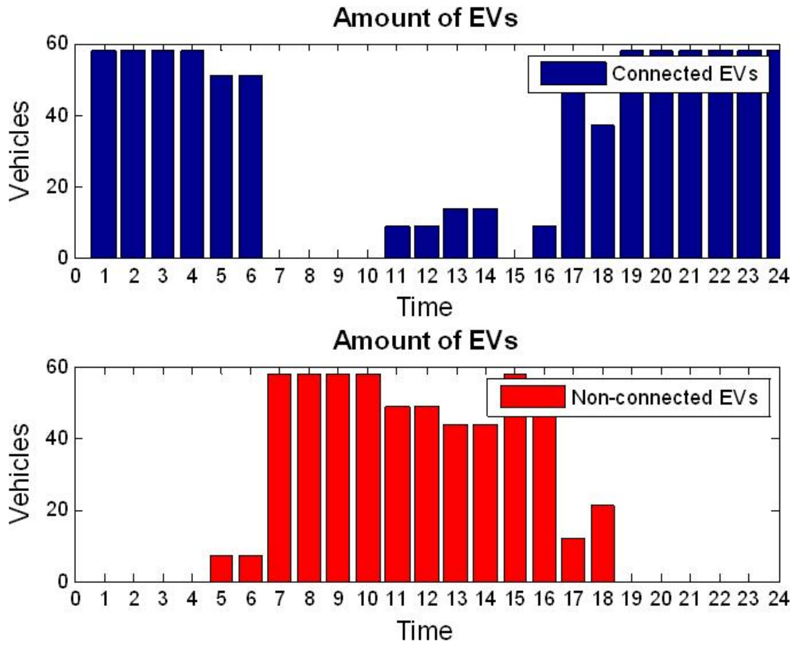

Figure 4.4: Distribution of connected and disconnected electric vehicles along the day based on the first random setup.

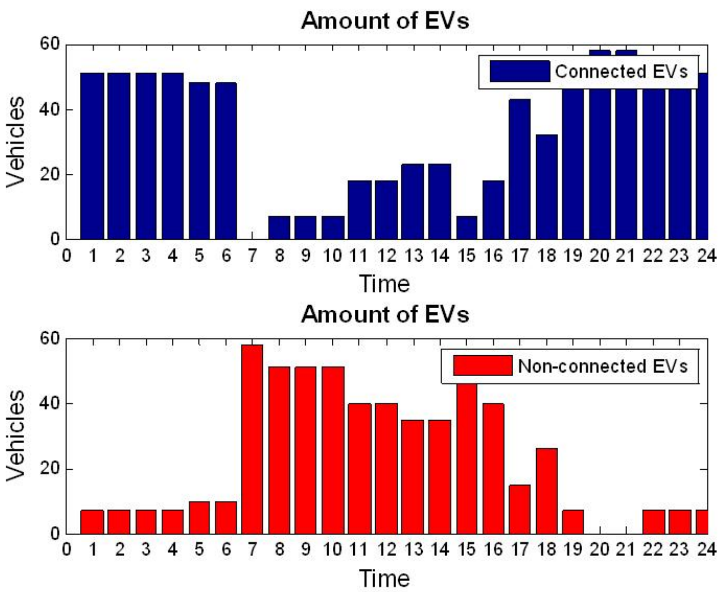

Figure 4.5: Distribution of connected and disconnected electric vehicles along the day based on the second random setup.

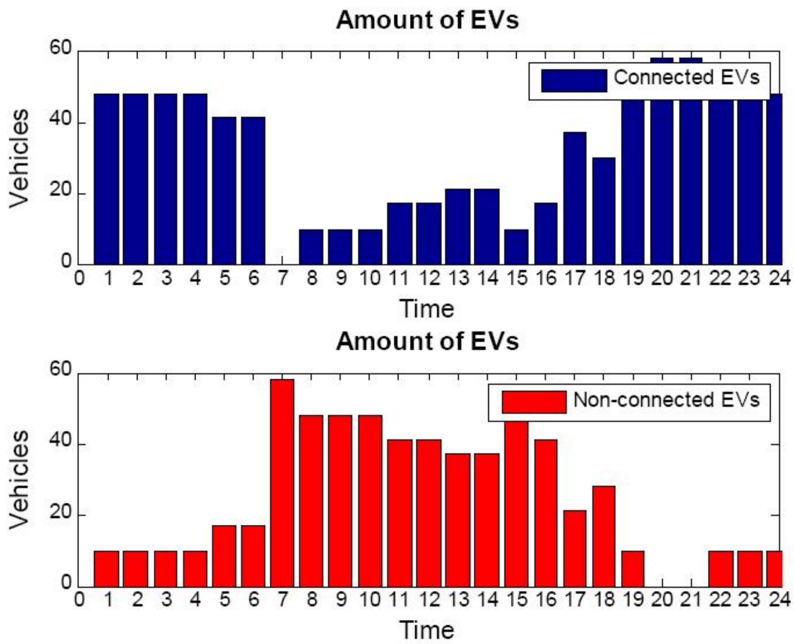

Figure 4.6: Distribution of connected and disconnected electric vehicles along the day based on the third random setup.

4.4 DIgSILENT PowerFactory Description

In this section a short description about the DIgSilent model of the distribution system can be found. However, this model is not was already built and it was used for the validation of the results as in the previous 8^{th} project.

The modelled system will consist of two different transformers, a total of 7 feeders and 231 end users connected through different types of cables. The whole system overview from the external grid built in DIgSILENT PowerFactory is shown on figure 4.7. More details and overviews of the different feeders can be found in appendix F on page A34.

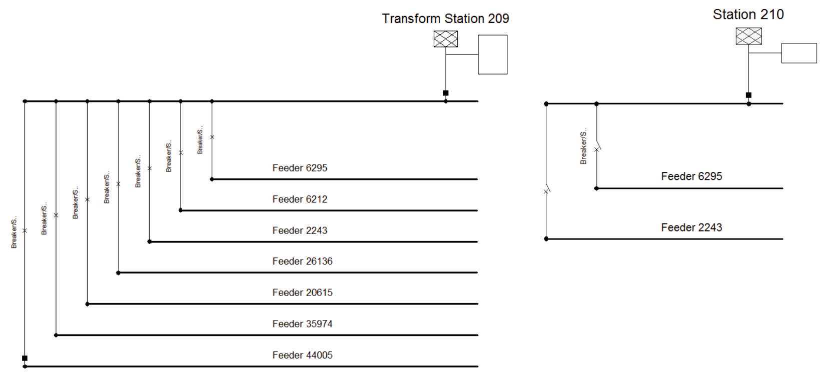

Figure 4.7: System overview in DIgSILENT PowerFactory software.

- Transformers

  Both transformers, named 209 and 210, are rated at 10.5/0.42 kV, having chosen a 400 KVA model. Their rated capacity is 400 kVA. Full load losses are set to a maximum of 4.5 kW, which makes only a 1,125% of the total capacity. The transformer operating under normal conditions is transformer 209. On the other hand, transformer 210 is usually off-line, suppliying power to the system only when there is a fault in the grid upstream of transformer 209.

Finally, it is important to remark that these transformers are modelled as the slack bus for the power flow equations. This means their angles will be the reference for any other variable [38].

- Cables

  The interconnections are made by twenty different cables of different dimensions. All cables are modelled taking the necessary data such as voltage and current capacity, resistance, reluctance, etc. from the NKT Teknisk katalog 2009 [45]. However, as not all types of cables were included in the catalogue, similar cables are used instead.

  For more information, all cable data used in the simulations can be seen in appendix E on page A32 [38].

- Feeders

  The system contains 7 feeders of various sizes and topologies. The main feeders are number 2243 and number 6295 as it can be seen in figure 4.7. Feeder number 2243 includes 26 loads distributed on eight sub terminals and a yearly consumption of 142.27 MWh, while feeder 6295 has 15 loads distributed on four sub terminals with a yearly consumption of 74,728 MWh.

  Feeder 6212 has 18 loads on six sub terminals, consuming 71.527 MWh. per year. Feeder 20615 contains 21 loads and 12 sub terminals. The total yearly consumption is 77.034 MWh. From the voltage point of view, this feeder is the most robust compared to the others because of the way it is interconnected with the transformer. This fact can be seen in the appendix F on page A34. Feeder 35974 includes 13 sub terminals to supply 57 different loads with a total yearly consumption of 260.657 MWh. Feeder 26136 is the smallest among all of them, with only 11 loads to be distributes on six sub terminal and a total yearly consumption of 56.122 MWh. On the contrary, feeder 44005 is the largest, having 83 loads, spread on 19 sub terminals and the total yearly consumption of 322.284 MWh [38].

- End users

  End users are modelled as a simple primary load. The hourly load was calculated from the yearly consumption according to the data given by the DSO and the hourly scaling factor provided by the web application Elforbrugs Panel [46]. This application gives different scaling factor for different types of end users. For this project, residential houses without electric heating were selected.

- Electric Vehicle

  EVs are represented by a secondary load next to every end user. By doing this, the residential house and the vehicle loads are separated but included in the same terminal feeder. In figure 4.8 the combination of both loads modelled in DIgSILENT PowerFactory 14.0 can be seen [38]. The EVs will be modelled as negative loads in the simulations when the batteries are discharging and they are supplying power back to the grid.

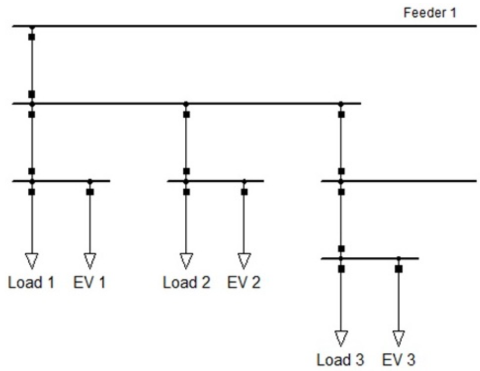

Figure 4.8: End users and Electric Vehicle model in DIgSILENT PowerFactory software.

5 Results

In this chapter the first thing to be presented are the results from the optimization algorithm for the three different days and for the three different random cases. After this the DIgSILENT PowerFactory simulation results for the hours when more EVs are charging and discharding in the distribution system will be analyzed. Finally, an economic analyses is performed in order to prove the value of the V2G technology.

5.1 Random Cases Optimized Results

The values of the technical parameters needed for running these simulations were described in section 4.3 on page 39, hourly prices for the three different days can be found in appendix D on page A26 while load data from the company "AKE El-Net Forsynings virksomhederne i aalborg" is not shown for privacy terms.

5.1.1 Simulated Case Nr. 1 Results

The first random case starts with the 58 EVs connected to the grid and by 07:00 in the morning they are all disconnected.

Please note the first column of all tables in this section represents the number of tens while the first row symbolizes the number of units. This way the 58 different EVs will be described.

5.1.1.1 Spring day

Tables 5.1 and 5.2 summarize the optimization algorithm output for the first random case during an average spring day. This day was chosen to be April 21^{st}, 2012 and the respective hourly prices can be seen in D.1 on page A26.

	0	1	2	3	4	5	6	7	8	9
0		4,5,6,14	5,6,17	4,5,6	5,6	5,6,17	6	6,13,14	4,5,6	5,6,19
1	4,5,6	5,6,14	5,6	4,5,6,14	5,6	4,5,6	5,6,19	5,6,17	3,4	5,6,17
2	4,5,17	5,6	5,6,17	5,6,17	6,14,17	5,6,17	5,6,19	5,6,17	5,6,13,14	5,6,17
3	5,6,17	5,6	6,17	5,6,14,17	5,6,14,17	5,6	6,14,17	5,6,14,17	5,6,19	5,6
4	4,5,6	5,6,17	6,14,17	5,6,19	5,6,14,17	5,6,13,14	5,6	4,5,6	5,6	5,6,19
5	5,6,19	5,6,19	5,6	5,6	5,6,13,14	4,5,6	5,6,17	5,6,17	5,6,17	

Table 5.1: Case Nr. 1, average spring day charging hours for the EVs

	0	1	2	3	4	5	6	7	8	9
0		21,22	22	22	-	21,22	-	21,22	22	21
1	-	11,17,22	21	11,17,22	21,22	-	21	22	22	22
2	22	-	21,22	22	11,21,22	21,22	21,22	21,22	22	22
3	11,21	21	22	11,12,21,22	11,21,22	-	11,22	11,21,22	21	-
4	22	21,22	11,17,22	21	11,12,21	21,22	-	22	21	21
5	21	21	21	-	21,22	-	21	21	22	

Table 5.2: Case Nr. 1, average spring day discharging hours for the EVs

It can be seen in table 5.1 the hours most in demand for charging are 05:00 and 06:00 in the morning, with 51 and 56 EVs respectively, as they are also the cheapest hours during the whole day.

On the other hand, the most chosen hours in table 5.2 for discharging the battery are 21:00 and 22:00, the most expensive ones at night. At 21:00, 30 EVs are giving energy back to the grid and by 22:00 the highest number of 33 EVs.

Moreover, due to the selected user profiles and their probability, many EVs come back and are connected again at 17:00 or at 19:00. It is at this precise cheaper moment when they are re-charged, storing the energy in order to discharge at the most expensive hours of the end of the day.

It is also important to remark quite a lot of EVs discharge partially their batteries at 11:00 because it is the most expensive hour of the day to save some money.

5.1.1.2 Summer day

Now tables 5.3 and 5.4 show the results for this random case during an average summer day. For this day hourly prices can be seen in D.2 on page A28 and July 21^{st}, 2011 was chosen.

	0	1	2	3	4	5	6	7	8	9
0		4,5,13	3,4,5	3,4,5	3,4	4,5	4,5	4,5,13	3,4,5	4,5
1	3,4,5	4,5,17	4,5	3,4,5	3,4,5	3,4	3,4,5	3,4,5	3,4	3,4
2	3,4,5	5	4,5	4,5	4,5,17	4,5	3,4,5	4,5	5	3,4,5
3	4,5,17	3,4	3,4,5	4,5,17	4,5,17	3,4,5	3,4,5,17	4,5,17	4,5	3,4,5
4	5	4,5,13	3,4,5,17	4,5	4,5	4,5,13	4,5	5	4,5	3,4,5
5	4,5	3,4,5	5	4,5	5,13	3,4	4,5	4,5	3,4,5	4,5

Table 5.3: Case Nr. 1, average summer day charging hours for EVs

	0	1	2	3	4	5	6	7	8	9
0		-	17	17,18	-	17	-	19	-	17
1	-	11,12	-	11,12	17	17	-	17	-	-
2	17	-	-	17	11,16	-	17	-	14	17
3	11,12	-	17	11,12	11	-	11,12	11	-	17
4	-	19	11,12	-	11,12	19	-	-	17	17
5	-	17	-	17	19	-	-	17	-	

Table 5.4: Case Nr. 1, average summer day discharging hours for the EVs

It can be seen in table 5.3 the favourite hours for charging the EVs are the cheapest ones for the summer day, 05:00 and 06:00, with 53 vehicles in both hours.

However, prices are not cheaper during the summer afternoon and summer evening than by the last hours of the day. The consequence is that most of the EVs do not charge their batteries in the meantime so they can not discharge either around 21:00 or 22:00 as in the previous case for the spring day.

For discharging the most chosen hours are 11:00, with up to ten vehicles, and 12:00, as these ones are the most expensive hours of the whole day. Also at 17:00, when many of the EVs get connected again to the grid and some of them discharge part of their remaining energy at the higher available price of the remaining day.

5.1.1.3 Christmas day

Tables 5.5 and 5.6 summarize the information about the EVs behaviour for the last Christmas day, 24^{th} of December 2011. Prices for this day are found in D.3 on page A30.

	0	1	2	3	4	5	6	7	8	9
0		5,6,14	5,6	4,5,6	5,6	4,5,6	5,6	5,6,14	5,6	5,6
1	5,6	5,6,13,14	5,6	6,13,14	4,5,6	5,6	5,6	4,5,6	3,4	4,5,6
2	5,6	5,6	4,5,6	5,6	5,6,14	5,6	5,6	6	5,6,14	5,6
3	5,6,14	3,4	5,6	5,6,14	5,6,14	5,6	4,5,6,13,14	5,6,14	5,6	4,5,6
4	5,6	5,6,14	5,6,13,14	5,6	5,6,14	5,6,14	5,6	5,6	5,6	6
5	4,5,6	5,6	5,6	4,5,6	5,6,14	3,4	4,5,6	5,6	5,6	

Table 5.5: Case Nr. 1, Christmas day charging hours for the EVs

	0	1	2	3	4	5	6	7	8	9
0		19	17	17,18	-	17	-	19,20	17	-
1	17	11,12,16,17	-	12,16,17	17	-	17	17	-	17
2	17	-	17	17	12,16,17	-	17	-	19,20	-
3	12,16,17	-	17	12,16,17	11,12,16,17	19	12,16,17	12,16,17	17	17
4	-	19,20	12,16,17	-	12,16,17	19	17	-	-	17
5	-	-	17	-	19	17	17	17	-	

Table 5.6: Case Nr. 1, Christmas day discharging hours for the EVs

It can be seen in table 5.5 the preferred hours for the EVs to be charged are once again 05:00 and 06:00 in the morning, when prices are much lower than at any other time.

Some of the vehicles also take advantage of being connected at 13:00 or at 14:00 so they can be charged, with the purpose of discharging at 16:00, 17:00 or 19:00 at a higher price.

Figure 5.1 shows a brief summary of the information presented for the random case number 1 comparing the three different days simultaneously.

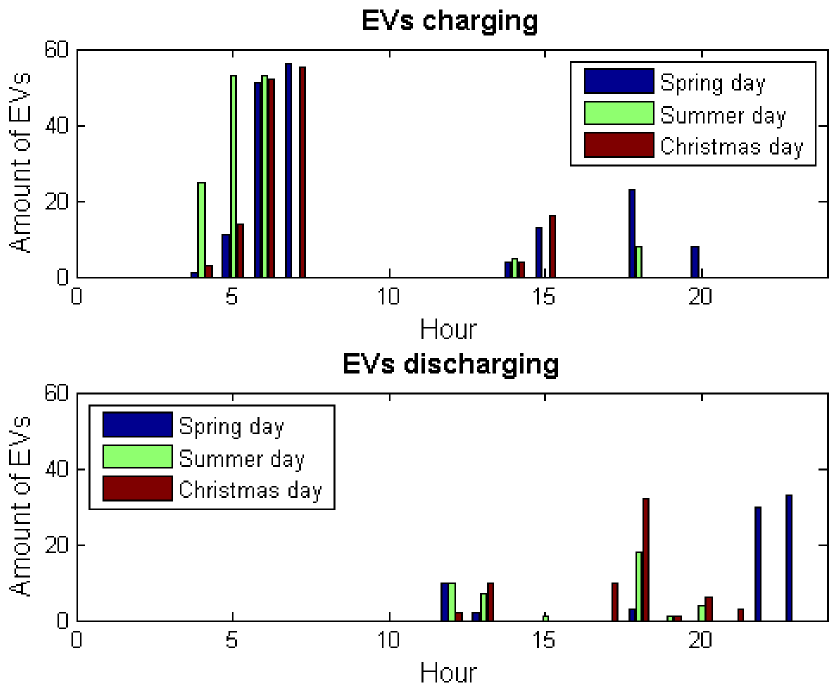

Figure 5.1: EVs charging and discharging hourly for the three different days for random case nr. 1.

As it can be seen the EVs are charged at the beginning of the day when prices are lower and discharged at a higher price, with the hour depending on the day. A second charging time takes place if it is economically convenient for them.

5.1.2 Simulated Case Nr. 2 Results

Now the results for the second random case simulations will be presented for the same three days as the previous one: average spring and summer days plus Christmas.

In this random case not all the EVs are initially connected, which means some EVs correspond to the user profile nr. 5. These results will be analyzed in deeper detail for every different day.

5.1.2.1 Spring day

Tables 5.7 and 5.8 show the charging and discharging hours during the spring day.

	0	1	2	3	4	5	6	7	8	9
0		5,6,19	6,13,17	5,6,13,14	3,4	13,20	4,5,17	5,6	5,6,13	5,6
1	12,13,20	4,5,6,19	5,6	13,20	5,6	5,6,14,17	5,6	4,5,6	5,6,13,17	5,6,14,17
2	5,6,13,17	5,6	5,6	5,6,13,17	5,6	4,5,6,19	5,6,19	5,6	5,6,13,14	5,6,13,17
3	5,6	4,5,6	6,13,17	5,6,13,14	12,20	13,20	5,6	6,14,17	4,5,6	5,6,13,14
4	4,5,6,19	5,6,19	5,6	12,13,20	6	5,6,18,19	5,6	6,13,17	5,6	5,6
5	5,6,19	5,19	3,4	5,6,19	5,6,19	13,20	4,5,6,19	5,6	5,6,19	

Table 5.7: Case Nr. 2, average spring day charging hours for the EVs

	0	1	2	3	4	5	6	7	8	9
0		21,22	11,12,22	21,22	-	11,12	21,22	22	11,12	-
1	11	21,22	21	11,12	21	11,12,21	-	21	11,12,21	11,12,21
2	11,12,21	-	-	11,12,21,22	-	21	21	-	21,22	11,12,21
3	-	21,22	11,12,21	21,22	11	11	-	11,12,21	21,22	21,22
4	21	-	21	11,12	-	21,22	21	11,12,21,22	-	-
5	22	21	-	21,22	21	11,12	21,22	-	21	

Table 5.8: Case Nr. 2, average spring day discharging hours for the EVs

The same charging and discharging behaviour as in the previous case can be seen in tables 5.7 and 5.8. EVs charge mostly at 05:00 and 06:00 in the morning due to the low prices and they discharge again at 21:00 and 22:00 when prices are higher.

Many of them recharge again once they are back during the evening in order to sell this energy at night as well.

Also the EVs connected to the grid by 11:00 take advantage of this fact for selling some of the energy stored in their batteries at the most expensive hour of the day.

One example of this are the profile nr. 5 users, such as EVs number 5, 10, 35 or 55 in this case. It can be seen that they are discharged at the most expensive hour to charge again inmediately after.

5.1.2.2 Summer day

The results for the random case nr. 2 for the summer day can be seen in tables 5.9 and 5.10.

	0	1	2	3	4	5	6	7	8	9
0		4,5	3,4,5	3,4,5	2,3,4	8,9,21	3,4,5	3,4,5	3,4,5	5
1	8,9,20,21	3,4,5	4,5	8,9,21	4,5	3,4,5	5	4,5	3,4,5	3,4,5
2	4,5	4,5	3,4,5	4,5	5	4,5	4,5	3,4,5	4,5	3,4,5
3	5	4,5	3,4,5	4,5	8,9	8,9	5	3,4,5	4,5	4,5
4	4,5	4,5	4,5	8,9	5	4,5	5	4,5	3,4	4,5
5	4,5	4,5	3,4	4,5	4,5	4,5	8,9,21	4,5	5	4,5

Table 5.9: Case Nr. 2, average summer day charging hours for the EVs

	0	1	2	3	4	5	6	7	8	9
0		17	11,12	13,14	-	10,11	17,18	17	11	-
1	11,12	17,18	17	11	-	11,12	-	17	11,12	11
2	11	17	17	11,12	17	-	17	17	13,14	11,12
3	-	17	11	13	11,12	12	-	11,12	-	14
4	17	17	-	10	-	17	17	17	-	-
5	17	-	-	17	17	11	-	-	17	

Table 5.10: Case Nr. 2, average summer day discharging hours for the EVs

As in the previous simulation for the summer day, the EVs charge their batteries early in the morning but do not discharge them by night. It was already explained the reason for this is not having a cheaper price during the day while connected prior to the night.

In addition to this, the hour when most EVs discharge is 17:00. This is because, according to the most probable user profile, the EVs are back and connected to the grid again by this time, which is the highest possible price before the end of the day. Apart from this, 11:00 and 12:00 are also ordinary hours to discharge, including 15 and 9 vehicles respectively each.

The seven profile nr. 5 EVs start charging as soon as they are connected to grid from 08:00 to 09:00 in order to sell this energy at higher prices at 10:00, 11:00 or 12:00 depending on the vehicle. After this, some of them are charged again before being disconnected at 21:00 because of the price and because they will need this energy for driving.

5.1.2.3 Christmas day

In tables 5.11 and 5.12 the charging and dishcarging results for the Christmas day simulations can be found.

	0	1	2	3	4	5	6	7	8	9
0		5,6	5,6	5,6	3,4	8	5,6	4,5,6	5,6	6
1	8	5,6	6	8	5,6	6	6	5,6	5,6	5,6
2	6	6	5,6	5,6	5,6	5,6	6	5,6	6	6
3	5,6	6	5,6	5,6	8,9	8	5,6	6	5,6	5,6
4	5,6	5,6	6	8,9	5,6	5,6	6	5,6	3,4	5
5	5,6	6	3,4	5,6	5,6	8,9	5,6	6	5,6	

Table 5.11: Case Nr. 2, Chrsitmas day charging hours for the EVs

	0	1	2	3	4	5	6	7	8	9
0		17,18	17	13	-	16	17	17,18	17	-
1	16	17	-	-	17	13	-	17	17	16,17
2	17	-	17	13	-	17	17	-	13	17
3	17	-	17	13	15,16	-	17	-	17	13
4	18	17	-	16	17	-	17,18	17	-	18
5	17	18	17	-	17	15,16	17	17	18	

Table 5.12: Case Nr. 2, Christmas day discharging hours for the EVs

Due to the low prices in the early morning, all the vehicles are charged between 03:00 and 09:00 in the morning depending on when they are connected. However, 48 of them will be charged at the cheapest hour, which is 05:00 for Christmas day. On the other hand, the hour when most EVs will be discharging is 17:00, specifically 28 of them.

It is important to state there is no second charging for any EV because of loading reasons. The demand without EVs for spring and summer days is lower compared to Christmas, so the transformer and cables loading is lower in the previous cases than this time.

About the profile nr. 5 EVs, it can be seen how they are all charging at 08:00 as it is their cheapest possible hour. Moreover, they discharge in case of having enough energy in the battery before being disconnected at 16:00, the highest price from their connection time.

As it was shown for the previous case, a comparison of the three different days for the second random case can be seen in figure 5.2.

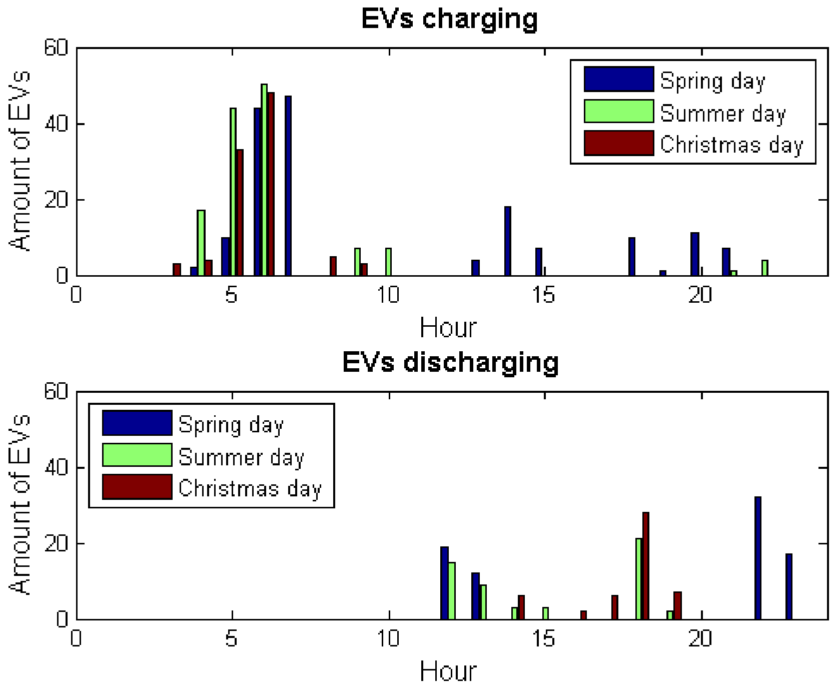

Figure 5.2: EVs charging and discharging hourly for the three different days for random case nr. 2.

Once again it is shown the EVs get charged in the early hours of the morning when prices are lower with independance of the day simulated. On the contrary, the different day and its respective hourly prices will be a key factor to determine the discharging hours.

5.1.3 Simulated Case Nr. 3 Results

In here the results for the last random case studied will be presented and analyzed.

5.1.3.1 Spring day

The charging and discharging hours for the last spring day simulation can be found in tables 5.13 and 5.14.

	0	1	2	3	4	5	6	7	8	9
0		5,6,13	3,4,19	8,14	3,4	5,6,19	3,4,19	5,6,19	5,6,14	5,6
1	5,6,13	5,6	8,14	5,6	8,14	5,6,19	8,14	5,6	5,6,14	8,14
2	5,6,14	5,6,13	5,6,13	5,6	5,6	3,4	5,6	5,6	5,6	5,6,14
3	5,6	5,6	3,4	5,6,14	5,6	6	5,6	5,6	8,14	8,14
4	8,14	5,6,19	5,6	3,4,19	5,6,19	8,14	5,6,19	3,4,19	8,14	5,6,19
5	5,6,19	6	5,6,19	5,6,19	5,6,19	5,6,14	5,6,19	5,6,14	5,6,19	

Table 5.13: Case Nr. 3, average spring day charging hours for the EVs

	0	1	2	3	4	5	6	7	8	9
0		21,22	21	20,21	-	21,22	21	21	11,21	21
1	21	-	21	21	21,22	21	21	-	11,21,22	21
2	11,21	21	21,22	21,22	-	-	21	21	21	11,21
3	-	-	-	11,21,22	21	-	21,22	21	20,21	20,21
4	20,21	21	-	21,22	21,22	21	21,22	21	20	21
5	21,22	-	21	21	21	11,21	21	11,21	21,22	

Table 5.14: Case Nr. 3, average spring day discharging hours for the EVs

Once again it is proved by tables 5.1 and 5.14 the hours most in demand for charging are 05:00 and 06:00 in the morning with 47 and 41 EVs each, while the preferred hours for discharging are 21:00 and 22:00 with 46 and 13 vehicles respectively.

As it was observed in the other spring day simulations, several EVs connected to the grid by 19:00 charge their batteries exploiting the price drop which occurs at this time. All this energy is sold right in the following hours as it can be seen in table 5.14 when the price has risen.

Other similarities with the previous spring day results are that some EVs discharge their batteries at 11:00 because of being the highest price during the day and that profile nr. 5 users start charging again at 08:00 for selling the remaining energy at 21:00, the most expensive possible hour for them.

5.1.3.2 Summer day

Tables 5.15 and 5.16 contain all the results for the summer day simulation for the third random case.

	0	1	2	3	4	5	6	7	8	9
0		4,5,13	3,4	8,9,21	3,4	4,5	3,4	4,5	4,5,17	4,5
1	4,5,13	4,5	8,9,21	4,5	8,9,21	4,5	8,9,21	4,5	4,5,17	8,9,21
2	4,5	4,5,13	4,5,13	4,5	4,5	3,4	4,5	4,5	4,5	4,5,17
3	4,5	4,5	3,4	4,5,17	4,5	4,5	4,5	4,5	8,9,21	8,9,21
4	8,9,21	4,5	4,5	3,4	4,5	8,9,21	4,5	3,4	8,9,21	4,5
5	4,5	5	4,5	4,5	4,5	4,5,17	4,5	4,5	4,5,17	

Table 5.15: Case Nr. 3, average summer day charging hours for the EVs

	0	1	2	3	4	5	6	7	8	9
0		19	-	10,11	-	17	19	-	11	17
1	19	17	11	-	11	17	11	17	11	11
2	11	19	-	17	-	19	17	-	-	11
3	17	-	19	11	17	17	17	17	11	-
4	11,12	17	-	-	17	11,12	17	-	11	17
5	17	17	17	-	17	11,12	-	11	19	

Table 5.16: Case Nr. 3, average summer day discharging hours for the EVs

From table 5.15 it is really clear the preferred hours for charging the battery are 04:00 and 05:00 in the morning with 47 and 42 vehicles each.

About table 5.16, 16 vehicles discharge at 11:00 when the price is at its maximum and 20 vehicles discharge at 17:00, when they go back home and get connected to the grid.

5.1.3.3 Christmas day

Last results for the Christmas day can be seen in tables 5.17 and 5.18.

	0	1	2	3	4	5	6	7	8	9
0		5,6	3,4	8,9	3,4	5,6	3,4	5,6	5,6,14	5,6
1	5,6	5,6	8,9	5,6	8,9	5,6	8,9	6	5,6,14	8,9
2	5,6,14	5,6	5,6	6	5,6	3,4	5,6	5,6	5,6	5,6,14
3	5,6	5,6	3,4	5,6,14	5,6	6	5,6	5,6	8,9	8,9
4	8,9	5,6	5,6	3,4	6	8,9	5,6	3,4	8,9	5,6
5	5,6	5,6	5,6	6	5,6	5,6,14	5,6	5,6,14	5,6	

Table 5.17: Case Nr. 3, Christmas day charging hours for the EVs

	0	1	2	3	4	5	6	7	8	9
0		19	-	16	19	17	-	17	12,17	17
1	19	17,18	15,16	17	16	17,18	16	-	12,17	16
2	17	19	-	17	-	19	-	17	17	12,17
3	-	17,18	-	12,17	17	-	17,18	17	16	15,16
4	16	17	17	19	-	16	17	19	16	17
5	-	17	17,18	-	17	12,17	17	12,17	-	

Table 5.18: Case Nr. 3, Christmas day discharging hours for the EVs

As in the Christmas day simulations for the previous cases, the hours most in demand for charging the EV according to table 5.17 are 05:00 and 06:00, when prices are lower.

On the contrary, it can be seen in table 5.18 10 EVs discharge at 16:00 while the highest amount of energy given back to the grid is at 17:00, with a total of 27 vehicles discharging.

Finally figure 5.3 shows the comparison of the results between the three different simulated days for the third random case.

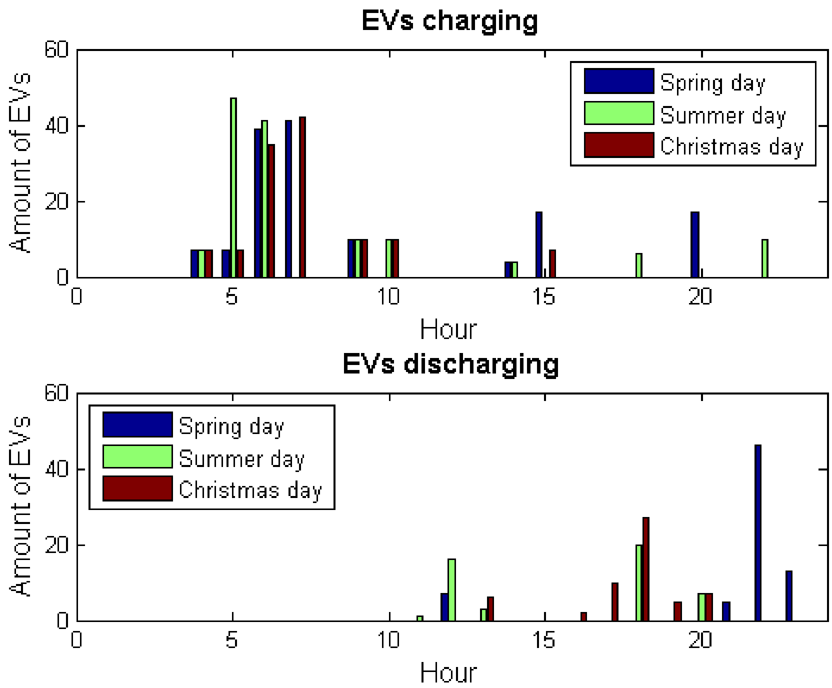

Figure 5.3: EVs charging and discharging hourly for the three different days for random case nr. 3.

Summarising, the EVs are charged in the morning at cheap electricity prices and discharged along the day at the hours when the prices are more suitable for selling the extra energy stored in the batteries.

5.2 Validation of Results in DIgSILENT PowerFactory

In this section the previous results from the optimization algorithm will be validated by using DIgSILENT PowerFactory simulations. The reason for this is to check the technical constraints of the distribution system when the EVs will be charging and discharging.

Four different locations will be simulated for the connected EVs distribution in the neighbourhood. These four EV distributions can be found in appendix **??** on page ??.

For these simulations the DIgSILENT PowerFactory network was described in section 4.4 on page 47 and it is important to remember the EVs discharging will be simply simulated as a negative load. Load data provided by the Distribution System Operator Company "AKE El-Net Forsynings virksomhederne i aalborg" can not be shown in the report nor in the DIgSilent file attached in the CD because of confidentiality.

Finally, the variables and parameters analyzed in the DIgSILENT PowerFactory result tables are the following: the precise hours simulated, the loading of the transformer under normal load conditions which is the same as with the first algorithm results, the total amount of EVs charging and discharging, the transformer loading including those EVs, the amount of overloaded cables after the simulation and the highest cable loading of the whole system.

5.2.1 Normal charging and discharging hours results

First of all, it is important to clarify the term “normal” is referring to those hours in which the number of EVs charging or discharging is not the highest during the day. According to this, in this new concept hours without any EV charging are together with other hours which have several EVs charging.

The reason for summarising all the information is that not all the results for 24 hours of the three different days and for the three random cases studied can be shown.

Nevertheless, the normal hours of the three different days for the three random cases were simulated and the most important result to be announced is that they didn’t exceed any technical constraint of the distribution system. Moreover, the same conclusion was obtained for the four different locations of the EVs in the map, although with slightly different results.

The hours with the second highest amount of EVs charging and discharging among the three cases simulated have been chosen to represent this group. The results with the EVs at the end of the radial can be seen in table 5.19 as an example.

	Spring day 17:00	Summer day 03:00	Christmas day 14:00
Transformer normal loading [MVA]	0,16	0,07	0,18
Number of EVs charging	Case 1 23	Case 1 25	Case 1 16
Transformer loading with EVs [MVA]	0,34	0,29	0,32
Amount of overloaded cables	-	-	-
Highest cable loading [%]	82	91	87
	Spring day 11:00	Summer day 11:00	Christmas day 16:00
Transformer normal loading [MVA]	0,11	0,12	0,20
Number of EVs discharging	Case 2 19	Case 2 15	Case 1 10
Transformer loading with EVs [MVA]	0,07	0,09	0,17
Amount of overloaded cables	-	-	-
Highest cable loading [%]	67	74	65

Table 5.19: DIgSILENT PowerFactory validation results for selected normal hours.

It can be verified in table 5.19 the selected normal hours with a higher amount of EVs charging correspond to case number 1. For the spring day, 23 EVs are charging at 17:00, for the summer day 25 EVs are charging at 03:00 in the morning while for Christmas only 16 will be charging at 14:00.

It can be also appreciated the loading of the transformer never exceeds the limit of 0,4 MVA. Moreover, the highest cables loading are also below 100% and the high values in the table are very related to the location setup, with all the EVs placed at the end of the radial.

About the discharging hours, it can be mentioned for spring and summer days they are both 11:00 with 19 and 15 EVs each but from a different case. For Christmas it will be 16:00 with 10 EVs discharging and data from case number 1.

However, it is clear none of them present any problems regarding the technical constraints.

5.2.2 Worst charging and discharging hours

After having verified the results of the normal hours, it is important to simulate the worst hours and to take a look at the amount of overloaded cables and the highest cable loading to verify if this charging and discharging plan can actually occur with the existing network.

According to the results from section 5.1 on page 51, the specific hours simulated with DIgSilent for the three random cases can be found in table 5.20.

	Spring day			Summer day			Christmas day		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Charging hours	06:00	06:00	06:00	04:00,05:00	05:00	04:00	06:00	06:00	06:00
Amount of EVs	56	47	41	53,53	50	47	55	48	42
Discharging hours	22:00	21:00	21:00	17:00	17:00	17:00	17:00	17:00	17:00
Amount of EVs	33	32	46	18	21	20	32	28	27

Table 5.20: Worst charging and discharging hours for the three cases in the three different days.

For the charging period, the worst hour chosen in the spring day has been 06:00 in the morning for case number 1. For summer day, the worst hour for the charging period is 05:00 from the second case. Lastly, for Christmas case number 1 results at 06:00 will be presented.

About the discharging times, the hours with more EVs have been also simulated. This way the results for the summer day are from case number 2 at 17:00 and from case nr. 1 at 17:00 for Christmas. For the spring day, although case number 3 has more EVs charging, case number 1 has been chosen to match it with the respective charging case.

The next set of tables contains information from different DIgSILENT PowerFactory simulations for the worst hours and for the different locations.

5.2.2.1 Location of EVs in setup Nr. 1

The EVs distribution in the neighbourhood map for this setup is in appendix C.1 on page A20 and the simulation results can be seen in table 5.21.

	Spring day 06:00	Summer day 05:00	Christmas day 06:00
Transformer normal loading [MVA]	0,12	0,11	0,14
Number of EVs charging	Case 1 56	Case 2 53	Case 1 55
Transformer loading with EVs [MVA]	0,45	0,47	0,47
Amount of overloaded cables	10	12	11
Highest cable loading [%]	156	140	178
	Spring day 22:00	Summer day 17:00	Christmas day 17:00
Transformer normal loading [MVA]	0,14	0,16	0,19
Number of EVs discharging	Case 1 33	Case 2 21	Case 1 32
Transformer loading with EVs [MVA]	0,09	0,11	0,12
Amount of overloaded cables	2	-	-
Highest cable loading [%]	62	59	68

Table 5.21: DIgSILENT PowerFactory validation results for selected worst hours in setup location nr. 1.

5.2.3 Location of the EVs in setup Nr. 2

The second EVs distribution can be found in appendix C.2 on page A21 and table 5.22 shows the simulation results.

	Spring day 06:00	Summer day 05:00	Christmas day 06:00
Transformer normal loading [MVA]	0,12	0,11	0,14
Number of EVs charging	Case 1 56	Case 2 53	Case 1 55
Transformer loading with EVs [MVA]	0,41	0,44	0,42
Amount of overloaded cables	8	13	7
Highest cable loading [%]	196	210	241
	Spring day 22:00	Summer day 17:00	Christmas day 17:00
Transformer normal loading [MVA]	0,14	0,16	0,19
Number of EVs discharging	Case 1 33	Case 2 21	Case 1 32
Transformer loading with EVs [MVA]	0,08	0,11	0,11
Amount of overloaded cables	-	-	-
Highest cable loading [%]	73	76	82

Table 5.22: DIgSILENT PowerFactory validation results for selected worst hours in setup location nr. 2.

5.2.4 Location of the EVs in setup Nr. 3

For the third setup, simulation results can be found in table 5.23 and the EVs distribution in appendix C.3 on page A22

	Spring day 06:00	Summer day 05:00	Christmas day 06:00
Transformer normal loading [MVA]	0,12	0,11	0,14
Number of EVs charging	Case 1 56	Case 2 53	Case 1 55
Transformer loading with EVs [MVA]	0,47	0,50	0,48
Amount of overloaded cables	9	12	12
Highest cable loading [%]	135	128	144
	Spring day 22:00	Summer day 17:00	Christmas day 17:00
Transformer normal loading [MVA]	0,14	0,16	0,19
Number of EVs discharging	Case 1 33	Case 2 21	Case 1 32
Transformer loading with EVs [MVA]	0,09	0,10	0,13
Amount of overloaded cables	-	-	-
Highest cable loading [%]	68	71	76

Table 5.23: DIgSILENT PowerFactory validation results for selected worst hours in setup location nr. 3.

5.2.5 Location of end of the radial

Finally, the simulation results from the setup where all EVs are placed at the end of the radial can be seen in table 5.24. The map for this distribution can be seen in appendix C.4 on page A23

	Spring day 06:00	Summer day 05:00	Christmas day 06:00
Transformer normal loading [MVA]	0,12	0,11	0,14
Number of EVs charging	Case 1 56	Case 2 53	Case 1 55
Transformer loading with EVs [MVA]	0,52	0,56	0,53
Amount of overloaded cables	22	18	24
Highest cable loading [%]	448	465	472
	Spring day 22:00	Summer day 17:00	Christmas day 17:00
Transformer normal loading [MVA]	0,14	0,16	0,19
Number of EVs discharging	Case 1 33	Case 2 21	Case 1 32
Transformer loading with EVs [MVA]	0,11	0,12	0,15
Amount of overloaded cables	-	-	3
Highest cable loading [%]	82	88	94

Table 5.24: DIgSILENT PowerFactory validation results for selected worst hours at the end of the radial.

It is clearly seen in tables 5.21, 5.22, 5.23 and 5.24 the four different setups exceed the transformer loading limit of 0,4 MVA. It can be aslo appreciated the worst setup is the one where the EVs are placed at the end of the radial, including a maximum transformer loading of 0,56 MVA.

The four different locations present as well simulation results with an amount of overloaded cables which is not negligible. In the best case, 7 cables are overloaded in the second setup for the Christmas day simulation at 06:00 while 55 EVs are charging. For the worst setup, again by placing the EVs at the end of the radial, 24 cables will be overloaded during the same Christmas hour simulation. By comparing the loading percentages it is proved the situation is worse when EVs are connected toward the end of the radial as losses will increase turning into cables extremely overloaded.

Although these results can not be admitted, it is also true this situation happens only once per day for the three different random cases studied. However, the rest of the results as well as the economic analysis described in the next section are still thought to be valid.

In order to avoid the result of overloading the transformer and the cables, a possible solution is suggested. It consists on adding a new constraint to the optimization algorithm to limit the maximum amount of EVs which can be simultaneously charging. After having introduced it, the expected result is that the EVs will be distributed across an interval, probably centered around the cheapest hour, instead of having all of them charging at one single hour.

Nevertheless the upper limit of this new constraint might be different for every day as it will depend on the normal loading of the transformer without EVs, so each case has to be individiually analyzed. This possible solution was investigated at the end of this project, but unfortunately there was no time to develop and to implement it. If this or any other type of restriction for the maximum amount of EVs charging can be modelled and included, it can be guaranteed the overloading limits of the system will not be exceeded again.

5.3 Economic Analysis

In this last section an economic analysis of the electric vehicles and the V2G technology will be carried out. The objective is to investigate the impact of the EVs in the electricity bills of normal Danish households. This affects to how much the power consumed might be increased because of charging the EV as well as to the possibility of earning some money when discharging it.

In order to perform the analysis, the two most important variables are the prices and the load data. It is important to remember the hourly prices without taxes can be seen in appendix D on page A26 but load data is not shown.

Firstly, the economic results about the total cost of the system are discussed. These numbers are obtained after having run the simulations for the different random cases. After this, a comparison of the cost only associated to the EVs is presented for two different economic possibilities regarding the discharge price of the EVs.

5.3.1 Distribution System Cost Results

The optimization algorithm results for the total cost of the distribution system for one day are presented here. The first optimization algorithm without any vehicle in the whole system and only including the normal load data will be used as a reference for comparing the EVs charging and discharging total costs.

For the first random case studied, table 5.25 shows the total daily cost of the system for the three different days simulated.

Please note all prices are expressed in euro (€).

	Random Case Nr. 1		
	Spring day	Summer day	Christmas day
Normal loading cost [€]	179,03	218,79	133,07
Cost including the EVs	225,25	267,26	152,06
Cost with V2G technology	198,82	251,18	134,68

Table 5.25: Total daily costs of the system for case nr. 1.

In the first row the total daily cost of the system without EVs can be seen. These costs are thought to be reasonable for a distribution system consisting of 231 loads. As an example, dividing the spring cost by the amount of households, multiplying it by 30 and applying the missing taxes in the electricity price to the result, an average house would be paying approximately 97 €/month in April.

However, it can be seen how the summer day is the most expensive one. This is due not only to the higher data values but also to the higher prices of this day.

The cost difference for having EVs charging in the system in the spring and summer days is very similar and very close to 50 €. On the other hand, for the Christmas day there is a difference smaller than 20 €. The reason for this small difference is that during the Christmas day almost all the EVs charge their batteries at the cheapest price from all the simulations.

It can be also verified the scenario when more money can be saved thanks to the V2G technology is the spring day. This is a logical result as it is precisely during this day when more EVs are giving energy back to the grid.

Results for random case number 2 can be seen in table 5.26

	Random Case Nr. 2		
	Spring day	Summer day	Christmas day
Normal loading cost [€]	179,03	218,79	133,07
Cost including the EVs	224,22	263,11	144,52
Cost with V2G technology	197,07	242,12	131,15

Table 5.26: Daily whole system.

In table 5.26 the same kind of results as those from the previous case can be seen. The cost of adding the EVs to the system is very similar for both spring and summer days. Moreover, once again the case when more money is saved is during the spring day because of the higher amount of EVs discharging.

As it was expected, the most expensive scenario is the system distribution for the summer day including the EVs charging.

It is curious although the total amount of money which is saved during Christmas is smaller than in the other two days, the final price for the system including V2G technology is even smaller than the one with only the normal loading cost. This means in this case the V2G technology enables the whole system to save money by managing in an intelligent and efficient way the energy which had come from the grid.

Table 5.27 summarises the results for the third random case simulated.

	Random Case Nr. 3		
	Spring day	Summer day	Christmas day
Normal loading cost [€]	179,03	218,79	133,07
Cost including the EVs	218,82	265,87	149,93
Cost with V2G technology	194,20	247,46	134,43

Table 5.27: Daily whole system.

For this case, the cost of adding the EVs to the system in the summer day is around 47 €while the amount of money saved by discharging the vehicles is almost 19 €.
This means most of the energy the EV batteries stored was used for running the vehicle rather than for selling it later.
The summer result really contrasts with the Christmas day, when the total cost of the system for Christmas including the V2G technology is very similar to the total cost of the systen without EVs.

However, the biggest money saving in absolute terms is for the spring day with all the EVs discharging for a total of 71 hours along the day.

Finally, a comparison between the hourly price and the fixed price defined in section 4.3.1 on page 39 was made. These results can be seen in table 5.28 only showing the cost associated to the EVs.

For these simulations, the EVs are paid at the respective hourly prices while charging but the energy coming from their batteries is accounted at a fixed price.

	Random Case Nr. 1		Random Case Nr. 2		Random Case Nr. 3	
	Hourly prices	Fixed price	Hourly prices	Fixed price	Hourly prices	Fixed price
Spring day	46,22	22,76	45,18	23,35	39,79	20,72
Summer day	48,47	14,59	44,32	18,86	47,08	16,72
Christmas day	18,99	13,56	11,45	10,38	16,86	12,07

Table 5.28: Costs associated to the EVs.

Firstly, it is important to remember the fixed price values used in this project are the statistical mean for the hourly prices for the different days. These values can be found in the price appendix D on page A26.

About the results, it is interesting how all values corresponding to the fixed price are always smaller for every case and at any simulated day. The reason for this is that the optimization algorithm determined the hours to discharge the battery based on the hourly price. If the amount of energy to be discharged is the same and at the same hours but finally multiplied by a smaller price, the total profit shall be smaller.

However, this
It is important to remark these results are just a first approach to the idea of the fixed price. Further studies should be carried out and this topic has to be really debated and investigated before deciding the future price for the energy coming back from the EVs batteries. Anyway, it is still considered as another good opportunity such as subsidies or taxes reduction to promote the electric vehicle among the population and to promote the V2G technology.

6 Conclusions

In this short master thesis an optimal charging and discharging algorithm for Electric Vehicles and a later verification of the results in a distribution system have been presented.

Firstly, an introduction explaining new European policies and research projects together with the concepts and parameters needed to understand this project was included in the problem analysis section. After this, the distribution system was described and the optimization algorithms were explained.

A first algorithm without EVs is run to determine the ordinary cost and the normal loading conditions of the distribution system. The results of this simulation are used as a reference for an economic analysis and the system loading conditions.

The second algorithm includes the electric vehicles and minimises the total cost of the system attending to economic criteria. From this simulation, an optimal charging and discharging hourly plan is obtained respecting all the technical constraints from the EVs.

About the results, the majority of EVs charge at the beginning of the day, which are also the cheapest hours. Once their batteries are charged, these EVs are disconnected and run discharging the battery until they are connected again. It is sometimes during these secondary or tertiary connection periods when discharging or intermediate charges take place. The reason for this last option is having enough energy stored in the battery for selling it some hours later by discharging, when the electricity price will be higher. By this intelligent and efficient management of the energy stored in the EVs battery, the final cost of the system as well as the total amount of power needed from the external grid is decreased.

However, this optimal planning still presents some technical issues regarding the DIgSILENT PowerFactory validation results. It is important to remark that for most of the simulated hours, the technical constraints such as exceeding the loading capacity of the transformer or the overloading of some of the cables were not violated. It is for the worst hours, when more EVs are charging simultaneously, that the transformer and some of the cables were overloaded.

As this only happens once a day or twice only for an specific day for a certain random case, the algorithm and the results are still thought to be valid. A possible solution suggested for avoiding this problem is modifying the algorithm code by adding a new technical constraint to limit the maximum amount of EVs charging at a time. By doing this, instead of trying to charge all the EVs at the same hour, they will be distributed along the cheapest hours interval. More ideas about how to improve this work are included in the “Future Work” section.

Regarding the economic analysis, the obtained results are thought to be very promising as the total cost of the system was always reduced by the use of the V2G technology. Moreover, this happened for the two different options tested: paying the energy at the corresponding hourly price or at the same fixed price for all the hours. For this project, the final value chosen for this parameter was the average daily price but this could be another debate topic taken into further discussion.

Summarising, for this economic reason it is highly recommended the V2G technology is implemented as soon as possible once the EVs penetration is noticeable and significant at distribution system levels.

7 *Future Work*

Despite the results obtained in this project are generally thought to be good, coherent and very promising especially from the economic point of view and for the V2G technology, there are still some ideas for future work.

The first thing to be introduced in the algorithm should be the new constraint in order to limit the maximum amount of EVs simultaneosuly connected and charging. By doing this, it could be assured the transformer will not be overloaded during the worst possible hours of the day.

However, this is not the only technical improvement which could be added to the project. It would be really interesting including all the technical constraints affecting a distribution system into the optimization algorithm. This way, the later DIgSILENT PowerFactory validation would not be necessary any more as it can be guaranteed all variables are within the limits. Once this is developed, the real optimal charging and discharging plan for all the EVs in the system would be achieved.

Some other ideas for the future work affect the different parameters used throughout this project.

The first possibility which could be investigated is increasing the amonut of EVs in the system. This is considered as something important because there is a total of 231 households in the negihbourhood for 58 vehicles, and the EV is expected to have a greater presence at a distribution level especially in a long-term future.

Related to this, new user profiles could be added to the model to make it closer to reality. Moreover, the definition of the user profiles could be replaced in a short future by connection and disconnection data from real consumers.

Another idea is studying some cases where the EVs have different battery characteristics. In a real distribution system, not all the customers will have the same electric vehicle, so studying new cases where different types of EVs are defined in order to ressemble real life can be interesting.

Last parameters to be modified for sensitivity analysis are the minimum and maximum values which limited if the battery could generate or could be recharged. The increase or the decrease of these two parameters will definitely affect the battery state of charge and the EV behaviour along the day, so further simulations about this could be done.

Finally, more economic analysis can be also carried out for a deeper exploration of the V2G technology and the saving of money at a costumer level.

8 *Summary*

In order to achieve the goals previously mentioned, the methodology proposed for this project is described in here.

During the first months of the second semester, a careful literature study including specific references and papers provided by the supervisors was carried out. After this study, the programming of the optimization algorithms was started and developed.

For this process it was chosen to use the General Algebraic Modeling System (GAMS) software because it is a high-level modeling system for mathematical programming and optimization. It consists of a language compiler, an optimization problem solver and it is also tailored for complex, large scale modeling applications **??**. It is because of these reasons that it was thought to be suitable for the optimization problem involved in this thesis.

During the development of the project, it was decided to implement two different algorithms. The first one will describe the distribution system wihtout the addition of any electric vehicle. Once it was verified to be working properly, the next step was including the necessary indeces, parameters, equations and constraints to model the EVs.

It is also important to mention for getting some of the parameters needed for the second algorithm, other softwares were used. This is the case of MATLAB® for the parameter containing the information about the connection and disconnection times along the day for all the EVs and also Microsoft Excel for dealing with West Denmark prices, directly obtained from the Danish TSO webpage.

To perform different simulations, three new random cases were created for this project using some files from the 8^{th} semester project. Moreover, these three different cases were simulated for three different representative days: average spring day, average summer day and Christmas day.

After running all the simulations, optimal charging and discharging hourly plans for the EVs were obtained. These results were validated in DIgSILENT PowerFactory in order to check the technical constraints of the distribution system.

In addition to this, the DIgSILENT PowerFactory validation of every case was run for the EVs having four diferent locations in the neoghbourhood map. The distribution for the four locations is attached as a map appendix.

All the results from simulations and validations were collected and presented in a suitable form for being thoughtfully analyzed. It is important to remark an unexpected result was obtained, so a possible solution for this specific problem was also suggested.

Finally, an economic analysis was carried out to check the viability of the V2G technology. In this section the simulations were run again to study the influence of the electricity price depending on the hourly price or on a fixed price.

All results from the optimization algorithm simulations, DIgSILENT PowerFactory validations and economic analysis can be found in the main report.

At the end of the semester all the information was gathered together and the final conclusions were written down in the report.

The date for the project delivery is the 31^{st} of May and the exam date is the 14^{th} of June.

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III APPENDIX

A MATLAB® code

A.1 Random distribution of EVs code

A.1.1 Initial_EVs

```
%% Initialization of the total amount of EV's charging according to
a Normal Distribution

evscharging=[]; % Total amount of EV's charging every hour.
noncharging=[]; % Total amount of EV's which are not charging every hour.
aux=[];

% evscharging=floor(normrnd(40,50,[1,time]))
% noncharging=aux-evscharging


% Parameters of the distribution:
mu=EV*0.9;
stand_dev=EV/10;

i=1;
aux=EV;
for i=1:1:time
    aux(i)=EV;
    evscharging(i)=floor(normrnd(mu,stand_dev));
    if evscharging(i)<20
         evscharging(i)=floor(normrnd(mu,stand_dev));
    end
    if evscharging(i)>EV
         evscharging(i)=floor(normrnd(mu,stand_dev));
    end
    noncharging(i)=aux(i)-evscharging(i);
end
```

A.1.2 Distribute_EVs

```
%% Random distribution of the initial state of the EV's.

plugged=ones(1,EV);
positions=[];
j=1;
```

```
for n=1:noncharging(j)
    position=floor(rand(1,1)*EV);
    while (plugged(position)==0)
        position=floor(rand(1,1)*EV);
    end
    plugged(position)=0;
    positions(n)=position;
end

[positions]=sort(positions) ;% Position of the EV's which start disconnected
in the plugged vector.
plugged; % Vector which contains the information of the initial state for
every EV.
```

A.1.3 Load_profile

```
%% Loading different user's profiles depending on the initial state and the
% probability we assigned to every profile.

aux1=rand(1,EV);
profile=[]; % Vector which informs us what profile will follow every EV.
example1=[];
example2=[];
example3=[];
example4=[];
example5=[];

for j=1:1:EV

    example1(1)=1;
    example2(1)=1;
    example3(1)=1;
    example4(1)=1;
    example5(1)=0;

   if ((plugged(1,j)==1) && aux1(1,j)<=0.6) % Profile Nr. 1: "Normal worker"
       profile(j)=1;
       for i=2:1:6
           plugged(i,j)=1;
           example1(i)=1;
       end
       for i=7:1:16
           plugged(i,j)=0;
           example1(i)=0;
       end
       for i=17:1:24
           plugged(i,j)=1;
           example1(i)=1;
       end
       i=0;
```

```
end
if ((plugged(1,j)==1) && aux1(1,j)>0.6 && aux1(1,j)<=0.7) % Profile Nr. 2:
    profile(j)=2;                                                "Hard worker"
    for i=2:1:4
        plugged(i,j)=1;
        example2(i)=1;
    end
    for i=5:1:18
        plugged(i,j)=0;
        example2(i)=0;
    end
    for i=19:1:24
        plugged(i,j)=1;
        example2(i)=1;
    end
    i=0;
end
if ((plugged(1,j)==1) && aux1(1,j)>0.7 && aux1(1,j)<=0.9) % Profile Nr. 3:
    profile(j)=3;      "Family with children" (Many times coming and leaving)
    for i=2:1:6
        plugged(i,j)=1;
        example3(i)=1;
    end
    for i=7:1:10
        plugged(i,j)=0;
        example3(i)=0;
    end
    for i=11:1:14
        plugged(i,j)=1;
        example3(i)=1;
    end
    for i=15:1:16
        plugged(i,j)=0;
        example3(i)=0;
    end
    for i=16:1:17
        plugged(i,j)=1;
        example3(i)=1;
    end
    for i=18:1:19
        plugged(i,j)=0;
        example3(i)=0;
    end
    for i=19:1:24
        plugged(i,j)=1;
        example3(i)=1;
    end
    i=0;
end
```

```
    if ((plugged(1,j)==1) && aux1(1,j)>0.9 && aux1(1,j)<=1) % Profile Nr. 4:
        profile(j)=4;                                       "Two periods time worker"
        for i=2:1:6
            plugged(i,j)=1;
            example4(i)=1;
        end
        for i=7:1:12
            plugged(i,j)=0;
            example4(i)=0;
        end
        for i=13:1:14
            plugged(i,j)=1;
            example4(i)=1;
        end
        for i=15:1:18
            plugged(i,j)=0;
            example4(i)=0;
        end
        for i=19:1:24
            plugged(i,j)=1;
            example4(i)=1;
        end
        i=0;
    end
    if (plugged(1,j)==0)   % Profile Nr. 5: "Night time worker"
        profile(j)=5;
        for i=2:1:7
            plugged(i,j)=0;
            example5(i)=0;
        end
        for i=8:1:16
            plugged(i,j)=1;
            example5(i)=1;
        end
        for i=17:1:19
            plugged(i,j)=0;
            example5(i)=0;
        end
        for i=20:1:21
            plugged(i,j)=1;
            example5(i)=1;
        end
        for i=22:1:24
            plugged(i,j)=0;
            example5(i)=0;
        end
        i=0;
    end
end
```

```
for i=1:1:time
    evscharging(i)=sum(plugged(i,:));
    evscharging(i)=evscharging(i)';
    noncharging(i)=aux(i)-evscharging(i);
end

USE=plugged';
```

B GAMS code

B.1 First algorithm

B.1.1 Distribution System Code

```
%% Initialization of the total amount of EV's charging according to
$FIRST OPTIMIZATION ALGORITHM

$ONTEXT
In here the total cost of the normal distribution system loading
will be calculated as a future reference for the EVs.
$OFFTEXT

SETS

p Number of hours to be simulated /H1,H2,H3,H4,H5,H6,H7,H8,H9,H10,H11,H12,H13,
                                   H14,H15,H16,H17,H18,H19,H20,H21,H22,H23,H24/

k Grid node  /K1,K2,K3,K4,K5,K6,K7,K8,K9/

m Next grid node /M1,M2,M3,M4,M5,M6,M7,M8,M9/

PARAMETERS

D(p) Electricity demand in period p  [kW]

         /
         .
         .
         .
         .
 ****CONFIDENTIAL DATA****
         .
         .
         .
         .
         /

PRICE(p) Electricity price in period p [cents \texteuro\kWh]

         /H1 0.5817          H13 0.7617
          H2 0.4587          H14 0.7574
```

```
          H3 0.4105          H15 0.7576
          H4 0.3105          H16 0.7562
          H5 0.3107          H17 0.7880
          H6 0.2930          H18 0.7876
          H7 0.3380          H19 0.7672
          H8 0.5372          H20 0.7440
          H9 0.6528          H21 0.7330
          H10 0.7555         H22 0.7220
          H11 0.7631         H23 0.7146
          H12 0.7667         H24 0.6624/

VARIABLES

Pin(p) Power supplied into the grid in period p [kW]

ct Total cost of the system [cents \texteuro]

POSITIVE VARIABLE Pin

EQUATIONS

OBJECTIVE     Total cost of the system. [DKK]
DEMAND(p)  Power produced equals to the demand. [kW]

OBJECTIVE .. ct=E=SUM((p),Pin(p)*PRICE(p));

DEMAND(p) .. Pin(p)=L=D(p);

MODEL OPTIMIZATION_ALGORITHM /ALL/

SOLVE OPTIMIZATION_ALGORITHM USING RMIP MINIMIZING ct;
```

B.2 Complete Model including the EVs

B.2.1 Distribution System and EVs Modelling GAMS Code

```
%% Initialization of the total amount of EV's charging according to
$SECOND OPTIMIZATION ALGORITHM

$ONTEXT
In this code, the EVs will be included along with the total cost of the normal
distribution system loading to minimise the total cost.
$OFFTEXT

SETS

p Number of hours to be simulated /H1,H2,H3,H4,H5,H6,H7,H8,H9,H10,H11,H12,H13,
                                  H14,H15,H16,H17,H18,H19,H20,H21,H22,H23,H24/
```

```
k Grid node  /K1,K2,K3,K4,K5,K6,K7,K8,K9/

m Next grid node /M1,M2,M3,M4,M5,M6,M7,M8,M9/

c EV fleet /C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15,C16,C17,C18,C19,
           C20,C21,C22,C23,C24,C25,C26,C27,C28,C29,C30,C31,C32,C33,C34,C35,C36,
           C37,C38,C39,C40,C41,C42,C43,C44,C45,C46,C47,C48,C49,C50,C51,C52,C53,
           C54,C55,C56,C57,C58/

PARAMETERS

D(p) Electricity demand in period p  [kW]

         /
         .
         .
         .
         .
 ****CONFIDENTIAL DATA****
         .
         .
         .
         .
         /

PRICE(p) Electricity price in period p [cents \texteuro\kWh]

         /H1 0.5817          H13 0.7617
          H2 0.4587          H14 0.7574
          H3 0.4105          H15 0.7576
          H4 0.3105          H16 0.7562
          H5 0.3107          H17 0.7880
          H6 0.2930          H18 0.7876
          H7 0.3380          H19 0.7672
          H8 0.5372          H20 0.7440
          H9 0.6528          H21 0.7330
          H10 0.7555         H22 0.7220
          H11 0.7631         H23 0.7146
          H12 0.7667         H24 0.6624/


MAXBAT(c) Maximum energy in an EV battery [kWh]

         /C1 35          C11 35          C21 35          C31 35          C41 35
          C2 35          C12 35          C22 35          C32 35          C42 35
          C3 35          C13 35          C23 35          C33 35          C43 35
          C4 35          C14 35          C24 35          C34 35          C44 35
          C5 35          C15 35          C25 35          C35 35          C45 35
```

```
          C6 35          C16 35          C26 35          C36 35          C46 35
          C7 35          C17 35          C27 35          C37 35          C47 35
          C8 35          C18 35          C28 35          C38 35          C48 35
          C9 35          C19 35          C29 35          C39 35          C49 35
          C10 35         C20 35          C30 35          C40 35          C35 35

          C51 35
          C52 35
          C53 35
          C54 35
          C55 35
          C56 35
          C57 35
          C58 35/

MINBAT(c) Minimum energy in an EV battery [kWh]

         /C1 0          C11 0          C21 0          C31 0          C41 0
          C2 0          C12 0          C22 0          C32 0          C42 0
          C3 0          C13 0          C23 0          C33 0          C43 0
          C4 0          C14 0          C24 0          C34 0          C44 0
          C5 0          C15 0          C25 0          C33 0          C45 0
          C6 0          C16 0          C26 0          C36 0          C46 0
          C7 0          C17 0          C27 0          C37 0          C47 0
          C8 0          C18 0          C28 0          C38 0          C48 0
          C9 0          C19 0          C29 0          C39 0          C49 0
          C10 0         C20 0          C30 0          C40 0          C50 0

          C51 0
          C52 0
          C53 0
          C54 0
          C55 0
          C56 0
          C57 0
          C58 0/

CONSUMPTION(c) Average EV battery energy comsumption while running [kWh\km]

         /C1 0.14       C11 0.14       C21 0.14       C31 0.14       C41 0.14
          C2 0.14       C12 0.14       C22 0.14       C32 0.14       C42 0.14
          C3 0.14       C13 0.14       C23 0.14       C33 0.14       C43 0.14
          C4 0.14       C14 0.14       C24 0.14       C34 0.14       C44 0.14
          C5 0.14       C15 0.14       C25 0.14       C35 0.14       C45 0.14
          C6 0.14       C16 0.14       C26 0.14       C36 0.14       C46 0.14
          C7 0.14       C17 0.14       C27 0.14       C37 0.14       C47 0.14
          C8 0.14       C18 0.14       C28 0.14       C38 0.14       C48 0.14
          C9 0.14       C19 0.14       C29 0.14       C39 0.14       C49 0.14
          C10 0.14      C20 0.14       C30 0.14       C40 0.14       C50 0.14
```

```
          C51 0.14
          C52 0.14
          C53 0.14
          C54 0.14
          C55 0.14
          C56 0.14
          C57 0.14
          C58 0.14/

DISTANCE(c) Average distance an EV runs per day & [km\day]

         /C1 42.7      C11 42.7      C21 42.7      C31 42.7       C41 42.7
          C2 42.7      C12 42.7      C22 42.7      C32 42.7       C42 42.7
          C3 42.7      C13 42.7      C23 42.7      C33 42.7       C43 42.7
          C4 42.7      C14 42.7      C24 42.7      C34 42.7       C44 42.7
          C5 42.7      C15 42.7      C25 42.7      C35 42.7       C45 42.7
          C6 42.7      C16 42.7      C26 42.7      C36 42.7       C46 42.7
          C7 42.7      C17 42.7      C27 42.7      C37 42.7       C47 42.7
          C8 42.7      C18 42.7      C28 42.7      C38 42.7       C48 42.7
          C9 42.7      C19 42.7      C29 42.7      C39 42.7       C49 42.7
          C10 42.7     C20 42.7      C30 42.7      C40 42.7       C50 42.7

          C51 42.7
          C52 42.7
          C53 42.7
          C54 42.7
          C55 42.7
          C56 42.7
          C57 42.7
          C58 42.7/

MAXSOCGEN(c) Maximum value of the function which limits if the battery
can generate or not [%]

         /C1 100        C11 100          C21 100          C31 100          C41 100
          C2 100        C12 100          C22 100          C32 100          C42 100
          C3 100        C13 100          C23 100          C33 100          C43 100
          C4 100        C14 100          C24 100          C34 100          C44 100
          C5 100        C15 100          C25 100          C35 100          C45 100
          C6 100        C16 100          C26 100          C36 100          C46 100
          C7 100        C17 100          C27 100          C37 100          C47 100
          C8 100        C18 100          C28 100          C38 100          C48 100
          C9 100        C19 100          C29 100          C39 100          C49 100
          C10 100       C20 100          C30 100          C40 100          C50 100

          C51 100
          C52 100
          C53 100
```

```
          C54 100
          C55 100
          C56 100
          C57 100
          C58 100/

MINSOCGEN(c) Minimum value of the function which limits if the battery can
generate or not [%]

         /C1 60         C11 60         C21 60         C31 60         C41 60
          C2 60         C12 60         C22 60         C32 60         C42 60
          C3 60         C13 60         C23 60         C33 60         C43 60
          C4 60         C14 60         C24 60         C34 60         C44 60
          C5 60         C15 60         C25 60         C35 60         C45 60
          C6 60         C16 60         C26 60         C36 60         C46 60
          C7 60         C17 60         C27 60         C37 60         C47 60
          C8 60         C18 60         C28 60         C38 60         C48 60
          C9 60         C19 60         C29 60         C39 60         C49 60
          C10 60        C20 60         C30 60         C40 60         C50 60

          C51 60
          C52 60
          C53 60
          C54 60
          C55 60
          C56 60
          C57 60
          C58 60/

MAXSOCCHAR(c) Maximum value of the function which limits if the battery can be
recharged or not [%]

         /C1 85         C11 85         C21 85         C31 85         C41 85
          C2 85         C12 85         C22 85         C32 85         C42 85
          C3 85         C13 85         C23 85         C33 85         C43 85
          C4 85         C14 85         C24 85         C34 85         C44 85
          C5 85         C15 85         C25 85         C35 85         C45 85
          C6 85         C16 85         C26 85         C36 85         C46 85
          C7 85         C17 85         C27 85         C37 85         C47 85
          C8 85         C18 85         C28 85         C38 85         C48 85
          C9 85         C19 85         C29 85         C39 85         C49 85
          C10 85        C20 85         C30 85         C40 85         C50 85

          C51 85
          C52 85
          C53 85
          C54 85
          C55 85
          C56 85
```

```
          C57 85
          C58 85/

MINSOCCHAR(c) Minimum value of the function which limits if the battery can be
recharged or not [%]

         /C1 0         C11 0        C21 0        C31 0        C41 0
          C2 0         C12 0        C22 0        C32 0        C42 0
          C3 0         C13 0        C23 0        C33 0        C43 0
          C4 0         C14 0        C24 0        C34 0        C44 0
          C5 0         C15 0        C25 0        C35 0        C45 0
          C6 0         C16 0        C26 0        C36 0        C46 0
          C7 0         C17 0        C27 0        C37 0        C47 0
          C8 0         C18 0        C28 0        C38 0        C48 0
          C9 0         C19 0        C29 0        C39 0        C49 0
          C10 0        C20 0        C30 0        C40 0        C50 0

          C51 0
          C52 0
          C53 0
          C54 0
          C55 0
          C56 0
          C57 0
          C58 0/

RATE(c) Charging\discharging rate to establish the amount of time needed to
charge\discharge the battery [1\h]

         /C1 3         C11 3        C21 3        C31 3        C41 3
          C2 3         C12 3        C22 3        C32 3        C42 3
          C3 3         C13 3        C23 3        C33 3        C43 3
          C4 3         C14 3        C24 3        C34 3        C44 3
          C5 3         C15 3        C25 3        C35 3        C45 3
          C6 3         C16 3        C26 3        C36 3        C46 3
          C7 3         C17 3        C27 3        C37 3        C47 3
          C8 3         C18 3        C28 3        C38 3        C48 3
          C9 3         C19 3        C29 3        C39 3        C49 3
          C10 3        C20 3        C30 3        C40 3        C50 3

          C51 3
          C52 3
          C53 3
          C54 3
          C55 3
          C56 3
          C57 3
          C58 3/
```

```
eta_charge(c) Battery charginng\discharging process efficiency [%]

         /C1 93          C11 93          C21 93          C31 93          C41 93
          C2 93          C12 93          C22 93          C32 93          C42 93
          C3 93          C13 93          C23 93          C33 93          C43 93
          C4 93          C14 93          C24 93          C34 93          C44 93
          C5 93          C15 93          C25 93          C35 93          C45 93
          C6 93          C16 93          C26 93          C36 93          C46 93
          C7 93          C17 93          C27 93          C37 93          C47 93
          C8 93          C18 93          C28 93          C38 93          C48 93
          C9 93          C19 93          C29 93          C39 93          C49 93
          C10 93         C20 93          C30 93          C40 93          C50 93

          C51 93
          C52 93
          C53 93
          C54 93
          C55 93
          C56 93
          C57 93
          C58 93/

eta_transport(c) EVs mechanical efficiency [%]

         /C1 86.5        C11 86.5        C21 86.5        C31 86.5        C41 86.5
          C2 86.5        C12 86.5        C22 86.5        C32 86.5        C42 86.5
          C3 86.5        C13 86.5        C23 86.5        C33 86.5        C43 86.5
          C4 86.5        C14 86.5        C24 86.5        C34 86.5        C44 86.5
          C5 86.5        C15 86.5        C25 86.5        C35 86.5        C45 86.5
          C6 86.5        C16 86.5        C26 86.5        C36 86.5        C46 86.5
          C7 86.5        C17 86.5        C27 86.5        C37 86.5        C47 86.5
          C8 86.5        C18 86.5        C28 86.5        C38 86.5        C48 86.5
          C9 86.5        C19 86.5        C29 86.5        C39 86.5        C49 86.5
          C10 86.5       C20 86.5        C30 86.5        C40 86.5        C50 86.5

          C51 86.5
          C52 86.5
          C53 86.5
          C54 86.5
          C55 86.5
          C56 86.5
          C57 86.5
          C58 86.5/

MINCHARGE(c) Minimum battery level for fleet c to be charged when an EV is going
to be used [%]

         /C1 20          C11 20          C21 20          C31 20          C41 20
          C2 20          C12 20          C22 20          C32 20          C42 20
```

```
          C3 20          C13 20          C23 20          C33 20          C43 20
          C4 20          C14 20          C24 20          C34 20          C44 20
          C5 20          C15 20          C25 20          C35 20          C45 20
          C6 20          C16 20          C26 20          C36 20          C46 20
          C7 20          C17 20          C27 20          C37 20          C47 20
          C8 20          C18 20          C28 20          C38 20          C48 20
          C9 20          C19 20          C29 20          C39 20          C49 20
          C10 20         C20 20          C30 20          C40 20          C50 20

          C51 20
          C52 20
          C53 20
          C54 20
          C55 20
          C56 20
          C57 20
          C58 20/

TABLE

USE(c,p) Binary condition to determine if the EV is being used (1) or connected (0)

           H1       H2       H3       H4       H5       H6       H7       H8       H9
C1         1        1        1        1        1        1        0        0        0
C2         1        1        1        1        1        1        0        0        0
C3         1        1        1        1        1        1        0        0        0
C4         1        1        1        1        1        1        0        0        0
C5         1        1        1        1        1        1        0        0        0
C6         1        1        1        1        1        1        0        0        0
C7         1        1        1        1        1        1        0        0        0
C8         1        1        1        1        1        1        0        0        0
C9         1        1        1        1        1        1        0        0        0
C10        1        1        1        1        1        1        0        0        0
C11        1        1        1        1        1        1        0        0        0
C12        1        1        1        1        1        1        0        0        0
C13        1        1        1        1        1        1        0        0        0
C14        1        1        1        1        1        1        0        0        0
C15        1        1        1        1        1        1        0        0        0
C16        1        1        1        1        1        1        0        0        0
C17        1        1        1        1        1        1        0        0        0
C18        1        1        1        1        0        0        0        0        0
C19        1        1        1        1        1        1        0        0        0
C20        1        1        1        1        1        1        0        0        0
C21        1        1        1        1        1        1        0        0        0
C22        1        1        1        1        1        1        0        0        0
C23        1        1        1        1        1        1        0        0        0
C24        1        1        1        1        1        1        0        0        0
C25        1        1        1        1        1        1        0        0        0
C26        1        1        1        1        1        1        0        0        0
```

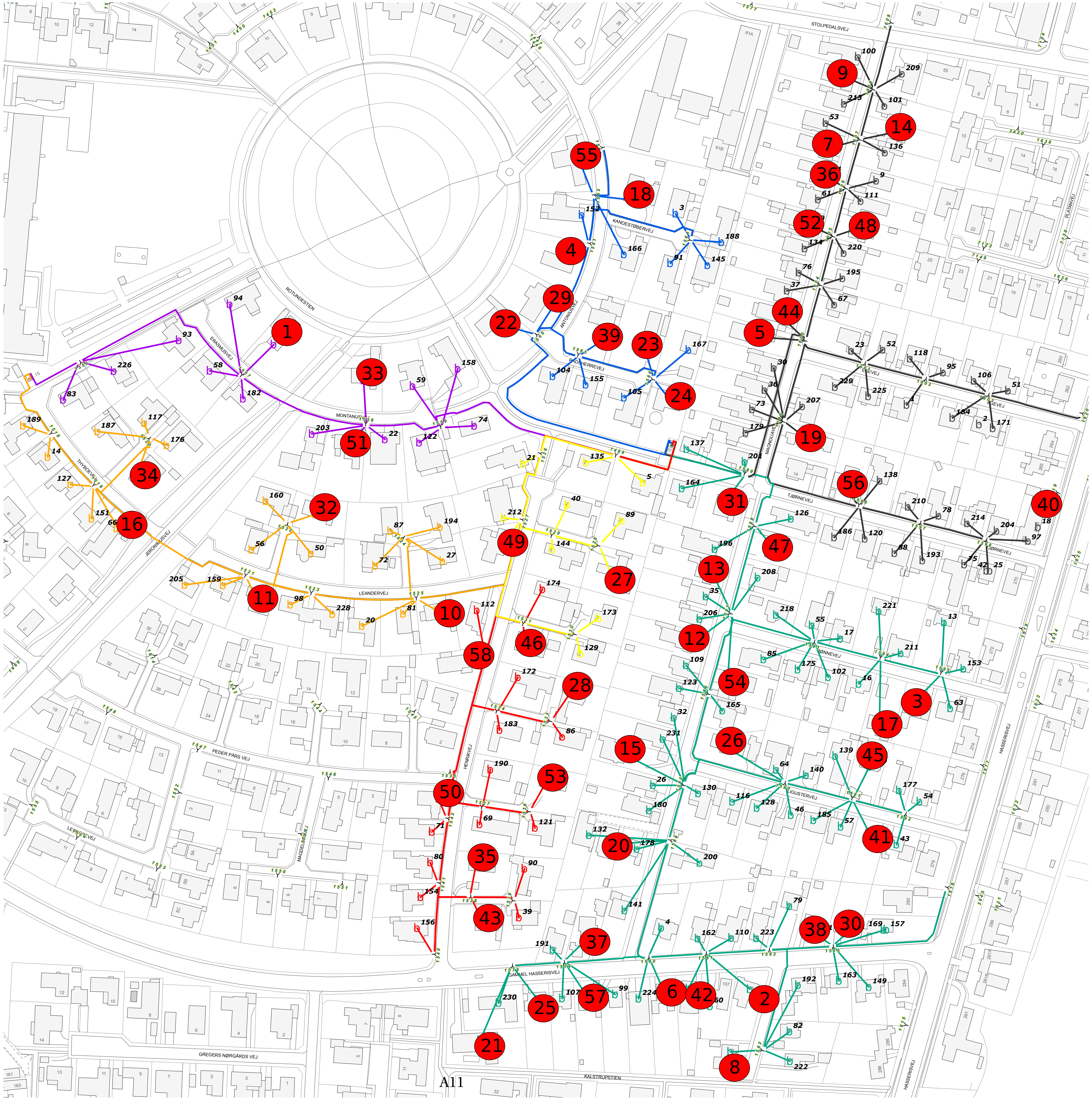
```
C27        1        1        1        1        1        1        0        0        0
C28        1        1        1        1        1        1        0        0        0
C29        1        1        1        1        1        1        0        0        0
C30        1        1        1        1        1        1        0        0        0
C31        1        1        1        1        0        0        0        0        0
C32        1        1        1        1        1        1        0        0        0
C33        1        1        1        1        1        1        0        0        0
C34        1        1        1        1        1        1        0        0        0
C35        1        1        1        1        1        1        0        0        0
C36        1        1        1        1        1        1        0        0        0
C37        1        1        1        1        1        1        0        0        0
C38        1        1        1        1        1        1        0        0        0
C39        1        1        1        1        1        1        0        0        0
C40        1        1        1        1        1        1        0        0        0
C41        1        1        1        1        1        1        0        0        0
C42        1        1        1        1        1        1        0        0        0
C43        1        1        1        1        1        1        0        0        0
C44        1        1        1        1        1        1        0        0        0
C45        1        1        1        1        1        1        0        0        0
C46        1        1        1        1        1        1        0        0        0
C47        1        1        1        1        1        1        0        0        0
C48        1        1        1        1        1        1        0        0        0
C49        1        1        1        1        1        1        0        0        0
C50        1        1        1        1        1        1        0        0        0
C51        1        1        1        1        1        1        0        0        0
C52        1        1        1        1        1        1        0        0        0
C53        1        1        1        1        1        1        0        0        0
C54        1        1        1        1        1        1        0        0        0
C55        1        1        1        1        0        0        0        0        0
C56        1        1        1        1        1        1        0        0        0
C57        1        1        1        1        1        1        0        0        0
C58        1        1        1        1        1        1        0        0        0


VARIABLES

Pin(p) Power supplied into the grid in period p [kW]

charge(c,p) Amount of energy charged in EV c battery in period p

generate(c,p) Amount of energy injected into the grid from EV c battery in period p

energy(c,p) Remaining energy charged in EV c battery at the end of period p

car(c,p) Variable to determine if the EV c battery can be charged from the grid (0)
or not (1) in period p

gen(c,p) Variable to determine if the EV c battery can generate power into the
grid (0) or not (1) in period p
```

```
cond(c,p) Variable to determine if the EV c battery is generating (1) or
charging (1) in period p

ct Total cost of the system [cents \texteuro]

POSITIVE VARIABLE Pin
POSITIVE VARIABLE charge
POSITIVE VARIABLE generate
POSITIVE VARIABLE energy
BINARY VARIABLE car
BINARY VARIABLE gen
BINARY VARIABLE cond

EQUATIONS

OBJECTIVE
DEMAND(p)
ENERG(c,p)
MAXENERGY(c,p)
MINENERGY(c,p)
ABC(c,p)
DEF(c,p)
EQUA(c,p)
EQUAT(c,p)
GENERATION(c,p)
CHARGING(c,p)
MINCHAR(c,p);

OBJECTIVE .. ct=E=SUM((p),Pin(p)*PRICE(p))-SUM((c,p),generate(c,p)*
*gen(c,p)*PRICE(p));

DEMAND(p) .. Pin(p)=L=D(p)+SUM((c),charge(c,p));

ENERG(c,p) .. energy(c,p)-energy(c,p-1)=E=((USE(c,p))*
*((generate(c,p)/eta_charge(c))-charge(c,p)*eta_charge(c))-
-(USE(c,p)-1)*CONSUMPTION(c)*DISTANCE(c)/eta_transport(c));

MAXENERGY(c,p) .. energy(c,p)=L=MAXBAT(c);

MINENERGY(c,p) .. energy(c,p)=G=MINBAT(c);

ABC(c,p) .. energy(c,p)/MAXBAT(c) + GENSOCMIN(c)=G=
gen(c,p)*GENSOCMIN(c);

DEF(c,p) .. energy(c,p)/MAXBAT(c) + GENSOCMIN(c) + EPS=L=
(1-gen(c,p))*(GENSOCMAX(c) - EPS);

EQUA(c,p) .. energy(c,p)/MAXBAT(c) + CHARSOCMIN(c)=L=
```

```
car(c,p)*CHARSOCMAX(c);

EQUAT(c,p) .. energy(c,p)/MAXBAT(c) + CHARSOCMIN(c) - EPS=G=
(1-car(c,p))*(CHARSOCMIN(c) - EPS);

GENERATION(c,p) .. generate(c,p)=L=(USE(c,p))*(1-gen(c,p))*
*(MAXBAT(c)/RATE(c))*cond(c,p);

CHARGING(c,p) .. charge(c,p)=L=(USE(c,p))*(1-gen(c,p))*
*(MAXBAT(c)/RATE(c))*(1-cond(c,p));

MINCHAR(c,p) .. energy(c,p)=G=MINCHARGE(c)*MAXBAT(c);

MODEL OPTIMIZATION_ALGORITHM /ALL/

SOLVE OPTIMIZATION_ALGORITHM USING RMIP MINIMIZING ct;
```

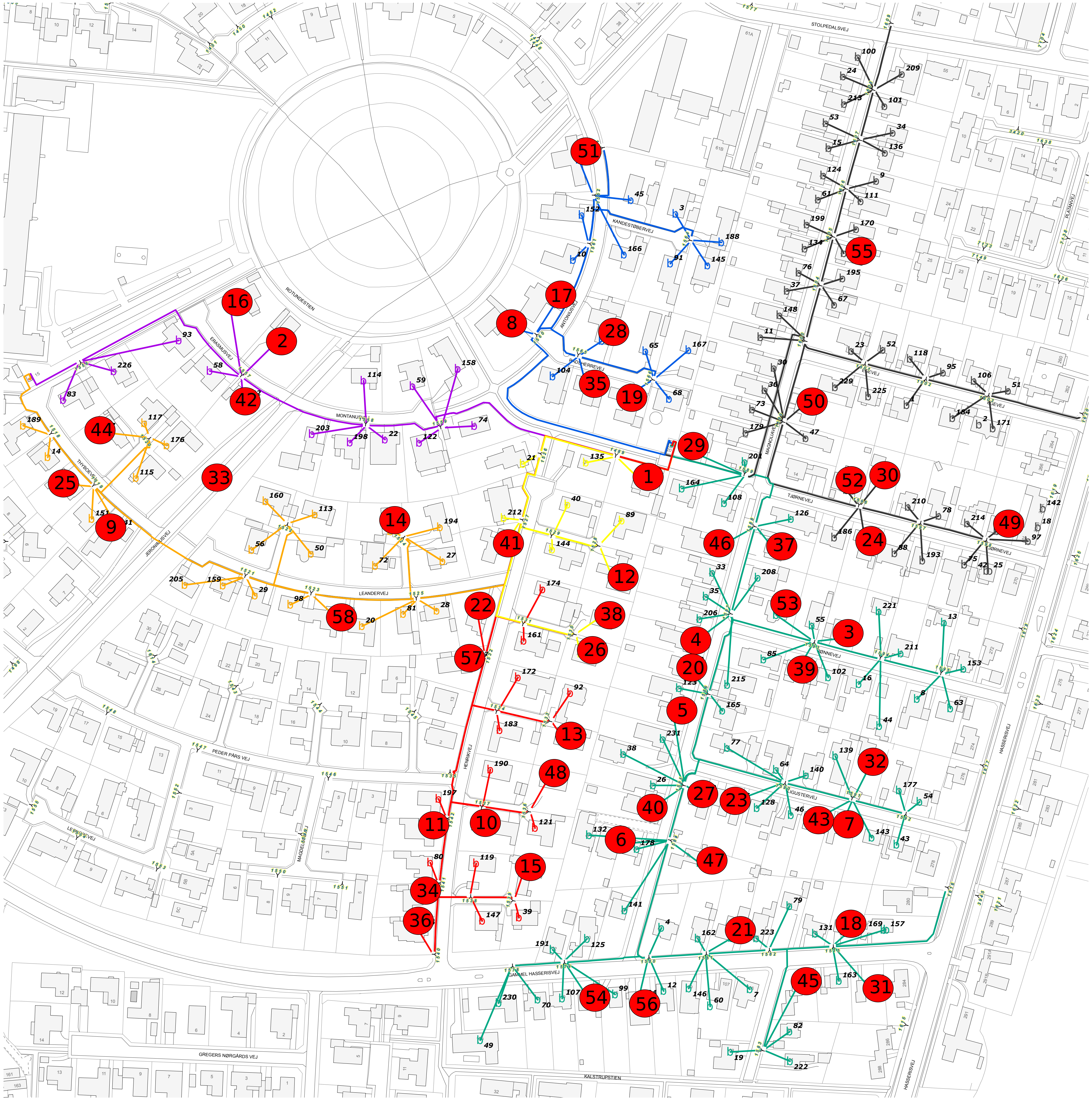
C Maps

C.1 Setup 1

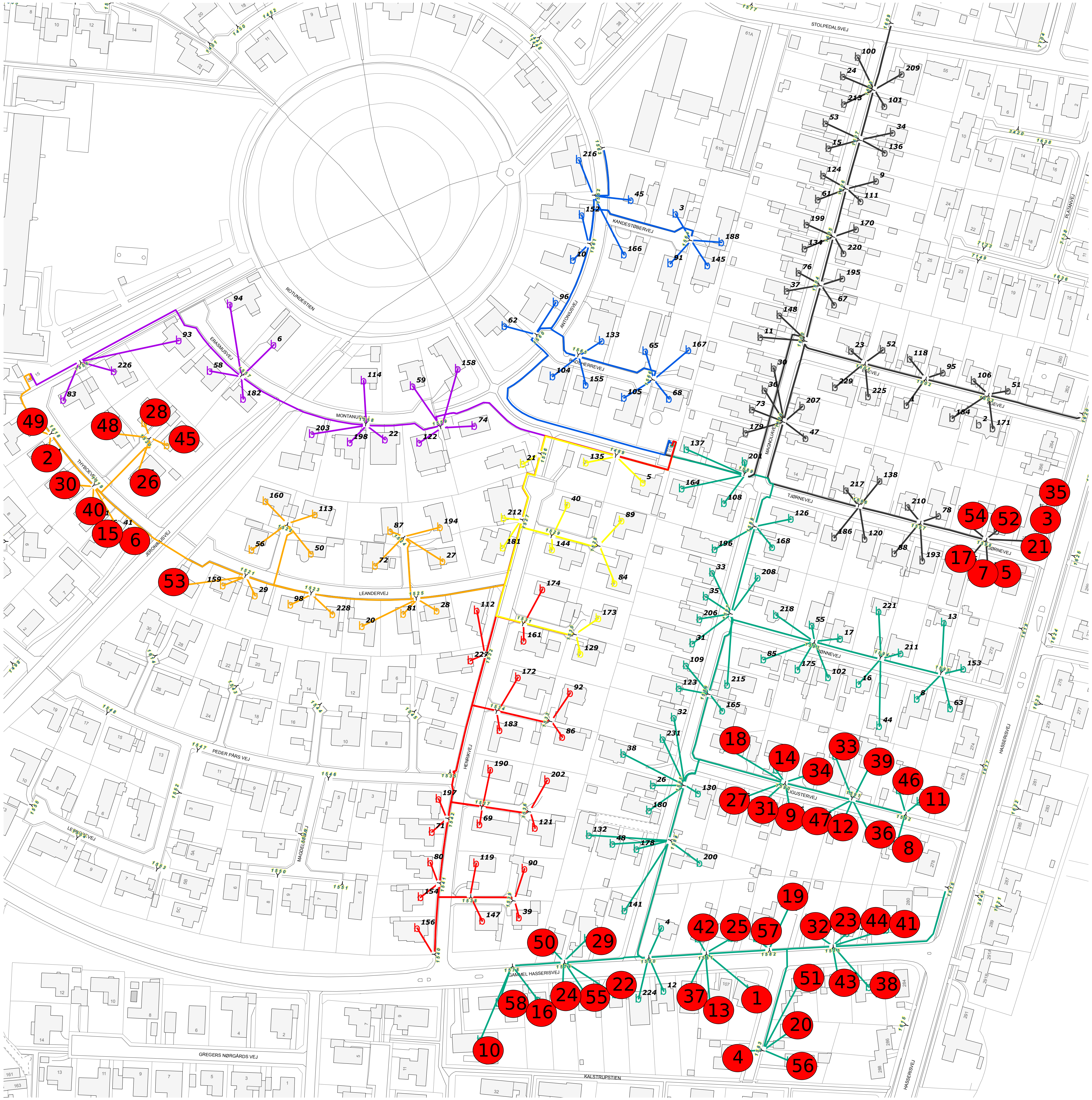


C.2 Setup 2

C.3 Setup 3



C.4 End of the radial setup



D Electricity Prices

In this appendix all electricity prices for West Denmark used in this project can be found. All data was collected from the Danish national TSO “Energinet”. [2]

D.1 Average Spring Day Prices

The day chosen as a reference for the spring hourly electricity prices is April 21st 2012.

Hour	Electricity Price (cents €/MWh)
1	0,7653
2	0,7631
3	0,7564
4	0,7428
5	0,7445
6	0,7404
7	0,7643
8	0,9096
9	0,9307
10	1,0037
11	1,0509
12	1,0032
13	0,8737
14	0,8330
15	0,8426
16	0,8555
17	0,8642
18	0,9001
19	0,8474
20	0,9468
21	1,0028
22	1,0028
23	0,9379
24	0,7655

Table D.1: Hourly electricity prices for 21/04/2012 in West Denmark [**?**].

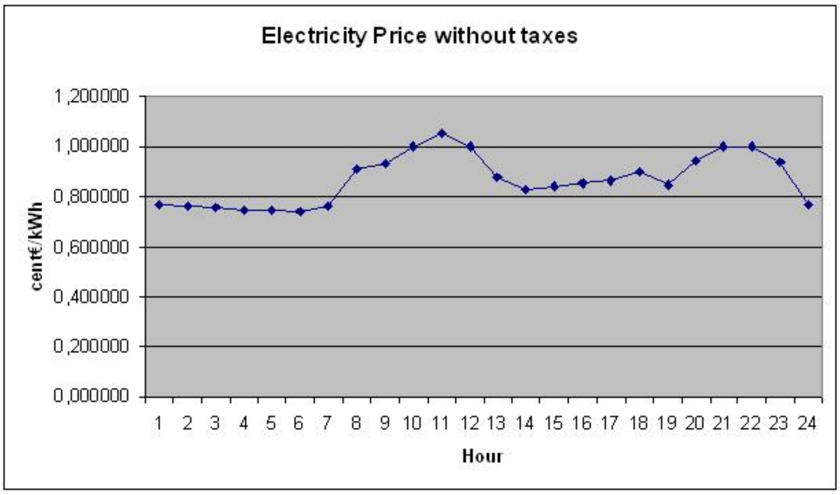


Figure D.1: Hourly electricity prices curve for 21/04/2012 in West Denmark [**?**].

The fixed price for the spring day is calculated according to equation D.1.

$$price' = \sum_p \frac{price_p}{24} = 0,8686 \frac{cents£}{kWh} \tag{D.1}$$

D.2 Average Summer Day Prices

For the summer hourly electricity prices, the reference day is July 21^{st} 2011.

Hour	Electricity Price (cents €/MWh)
1	0,5817
2	0,4587
3	0,4105
4	0,3105
5	0,3107
6	0,2930
7	0,3380
8	0,5372
9	0,6528
10	0,7555
11	0,7631
12	0,7667
13	0,7617
14	0,7574
15	0,7576
16	0,7562
17	0,7880
18	0,7876
19	0,7672
20	0,7440
21	0,7330
22	0,7220
23	0,7146
24	0,6624

Table D.2: Hourly electricity prices for 21/07/2011 in West Denmark [?].

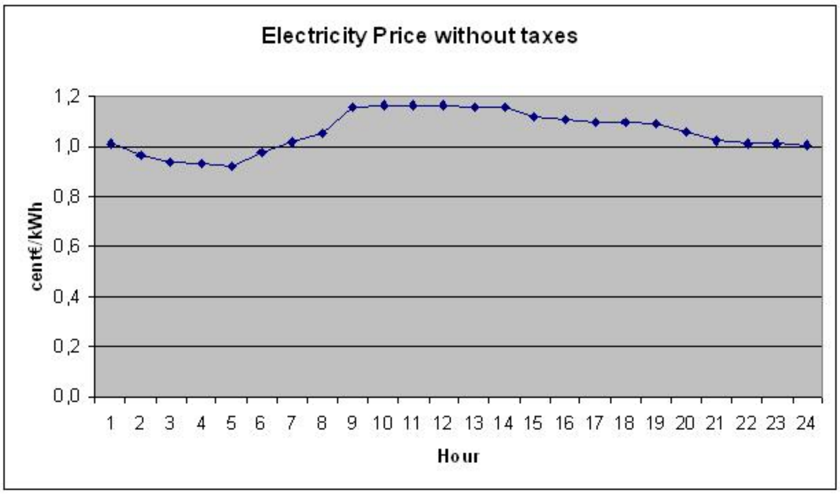


Figure D.2: Hourly electricity prices curve for 21/07/2011 in West Denmark [?].

The summer day fixed price is calculated as the mean for the hourly prices. The result can be seen in equation D.2.

$$price' = \sum_p \frac{price_p}{24} = 1,0593 \frac{cents£}{kWh} \tag{D.2}$$

D.3 Christmas Day Prices

Christmas day prices for simulations was collected on the December 24^{th} 2011.

Hour	Electricity Price (cents €/MWh)
1	0,5817
2	0,4587
3	0,4105
4	0,3105
5	0,3107
6	0,2930
7	0,3380
8	0,5372
9	0,6528
10	0,7555
11	0,7631
12	0,7667
13	0,7617
14	0,7574
15	0,7576
16	0,7562
17	0,7880
18	0,7876
19	0,7672
20	0,7440
21	0,7330
22	0,7220
23	0,7146
24	0,6624

Table D.3: Hourly electricity prices for 24/12/2011 in West Denmark [?].

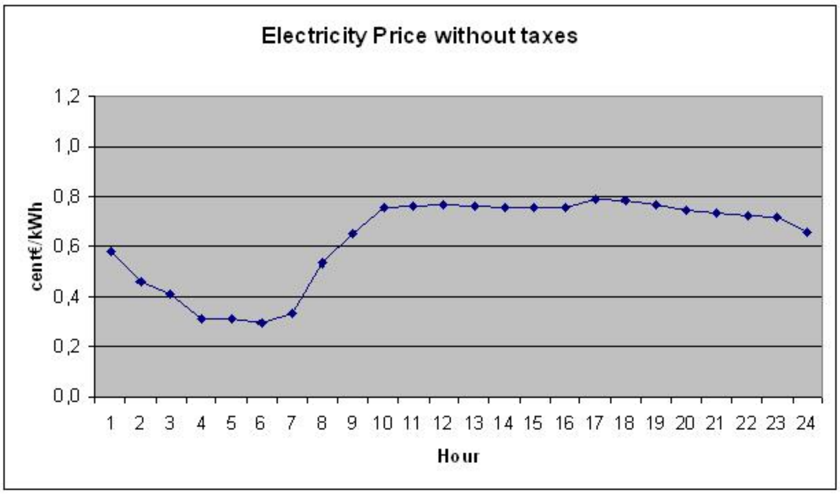


Figure D.3: Hourly electricity prices curve for 24/12/2011 in West Denmark [?].

Equation D.3 shows the fixed price calculated for the Christmas day.

$$price' = \sum_{p} \frac{price_p}{24} = 0,6304 \frac{cents£}{kWh} \tag{D.3}$$

E Cable data

Cable	rated voltage (kV)	Rated current (kA)	R (Ohm/km)	X (Ohm/km)
APB 150	12	0,23	0,126	0,084
APB 16	12	0,067	1,15	0,085
APB 25	12	0,086	0,728	0,086
APB 35	12	0,103	0,525	0,082
APB 50	12	0,122	0,389	0,084
APB 6_0	12	0,039	3,08	0,087
PSP 10	1	0,052	1,83	0,089
PSP 150_50	1	0,23	0,208	0,084
PSP 240_95	1	0,297	0,128	0,083
PSP 50_35	1	0,122	0,641	0,084
PSP 6	1	0,039	3,08	0,094
PVIK 10	1	0,052	1,83	0,089
PVIK 120	1	0,203	0,155	0,082
PVIK 16	1	0,067	1,15	0,085
PVIK 25	1	0,086	0,728	0,086
PVIK 35	1	0,103	0,525	0,082
PVIK 6	1	0,039	3,08	0,089
PVIKS 16	1	0,067	1,15	0,085
PVIKS 25	1	0,086	0,728	0,086
PVIKS 6	1	0,039	3,08	0,089

Table E.1: Cable data for DIgSILENT PowerFactory simulations

F DIgSILENT PowerFactory Model

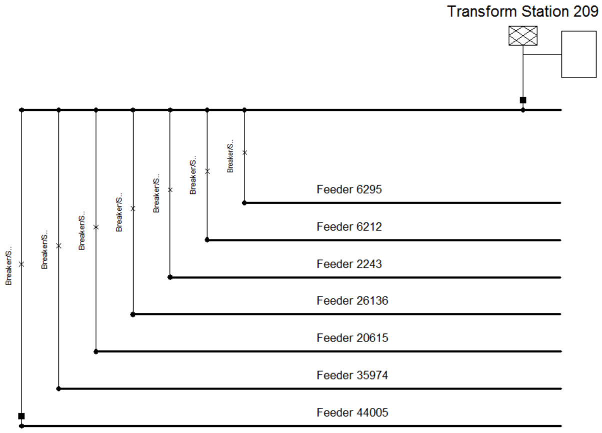


Figure F.1: Transformer 209

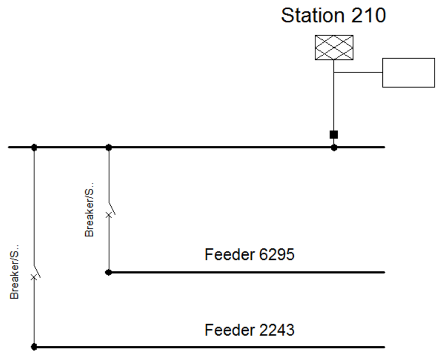


Figure F.2: Transformer 210

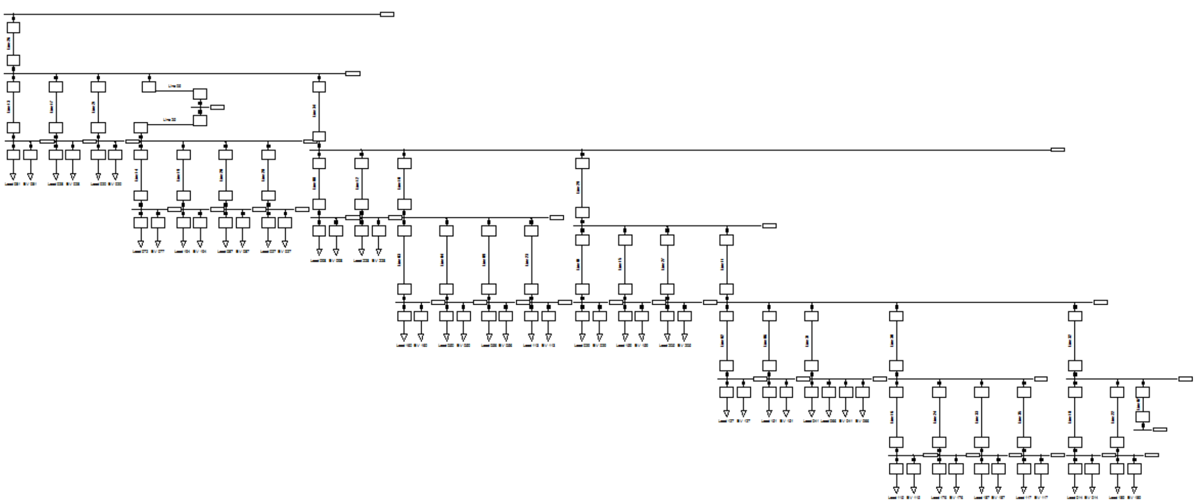


Figure F.3: Feeder 2243

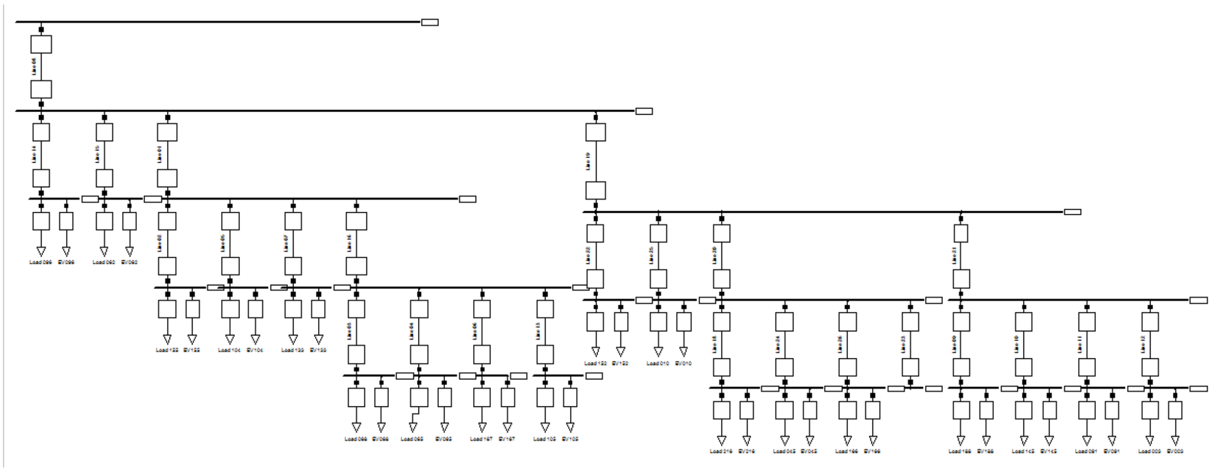


Figure F.4: Feeder 6112

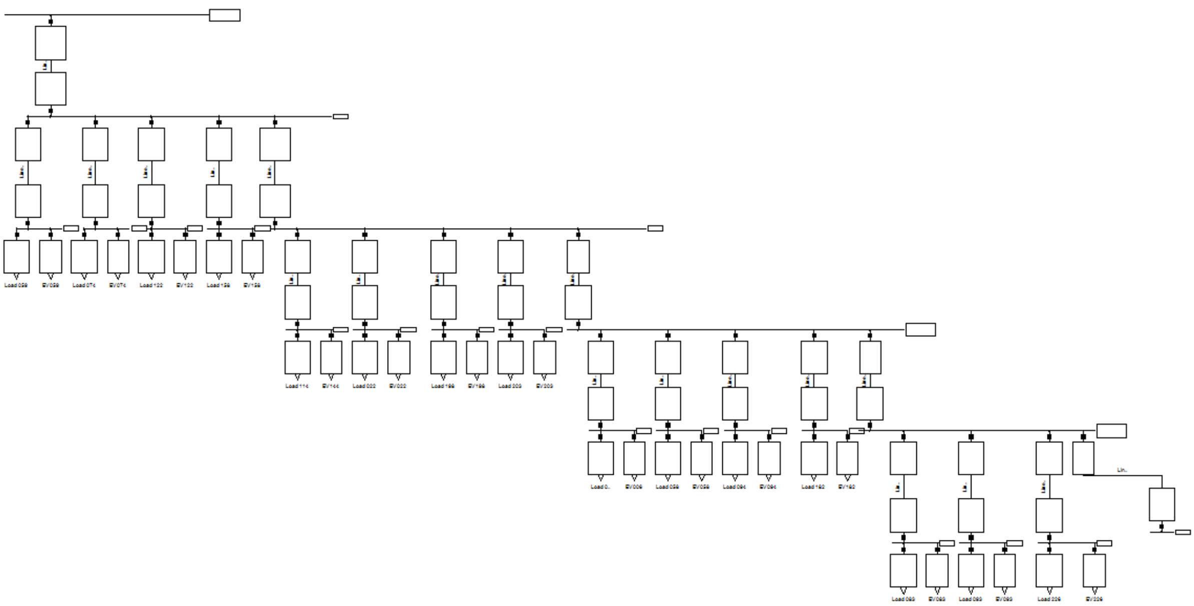


Figure F.5: Feeder 6295

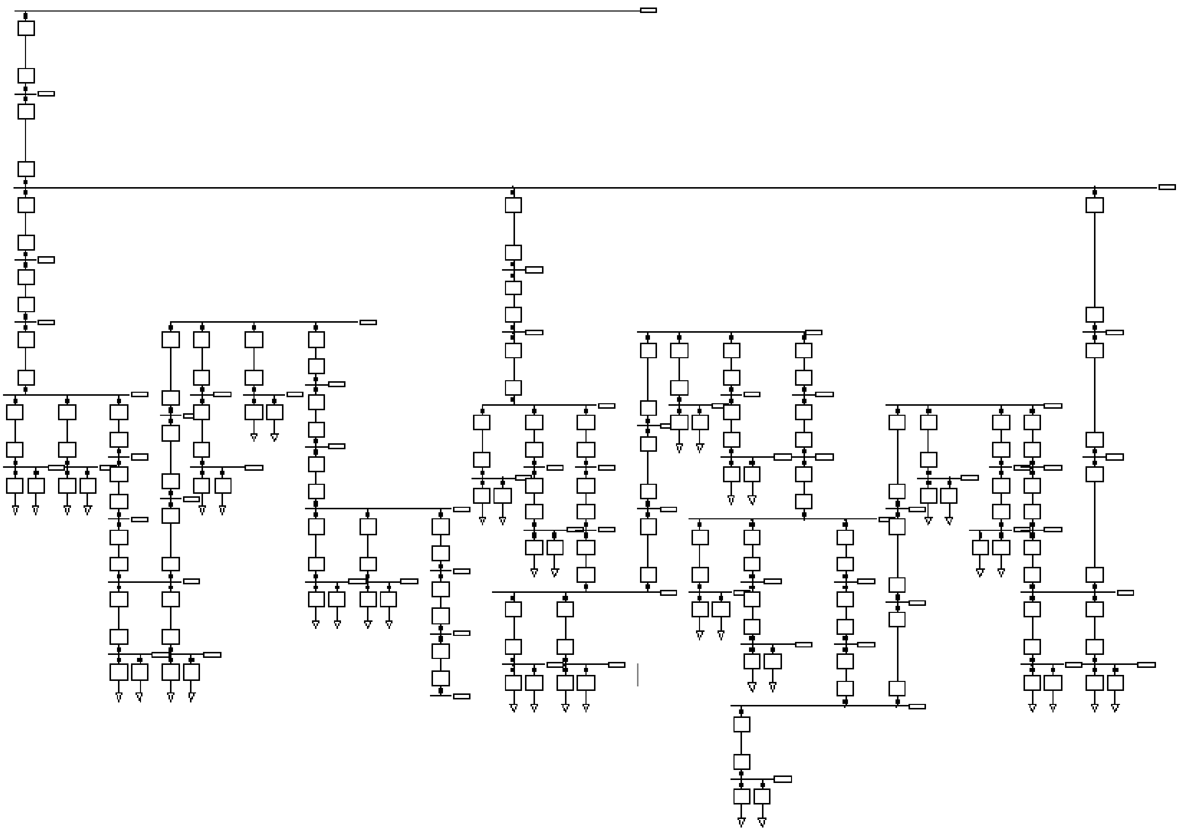


Figure F.6: Feeder 20615

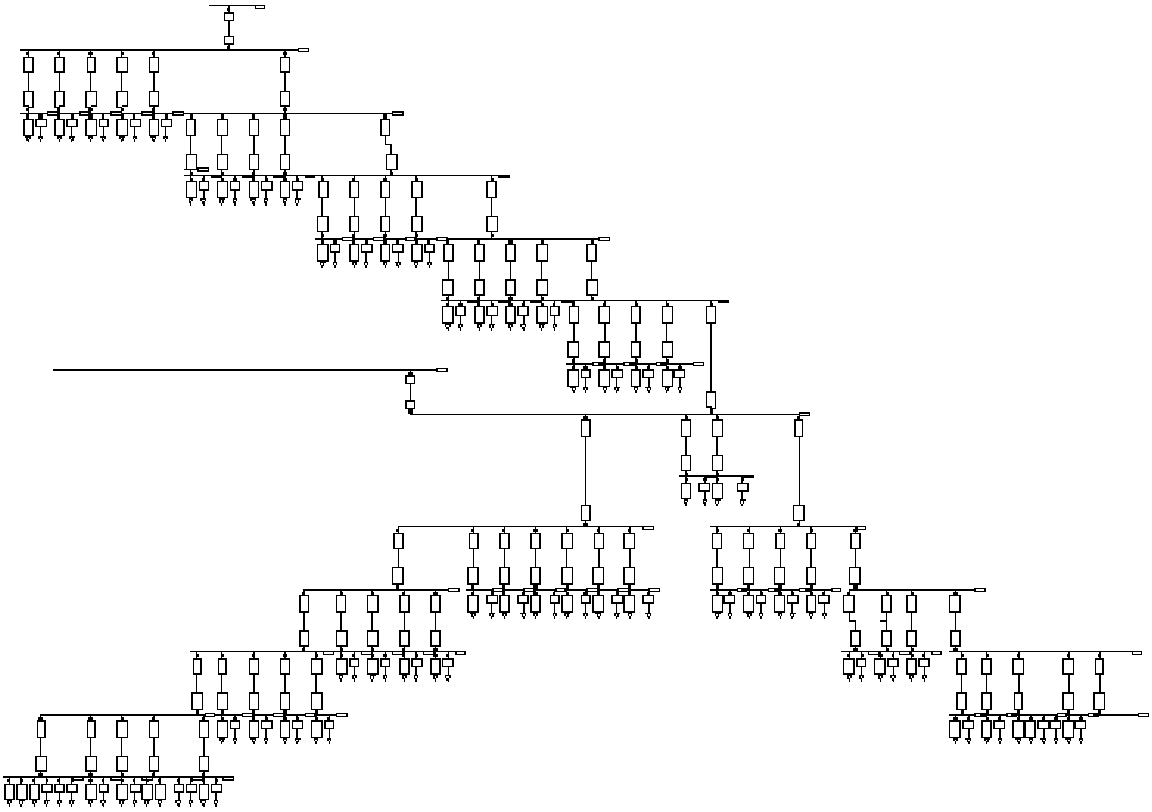


Figure F.7: Feeder 35974

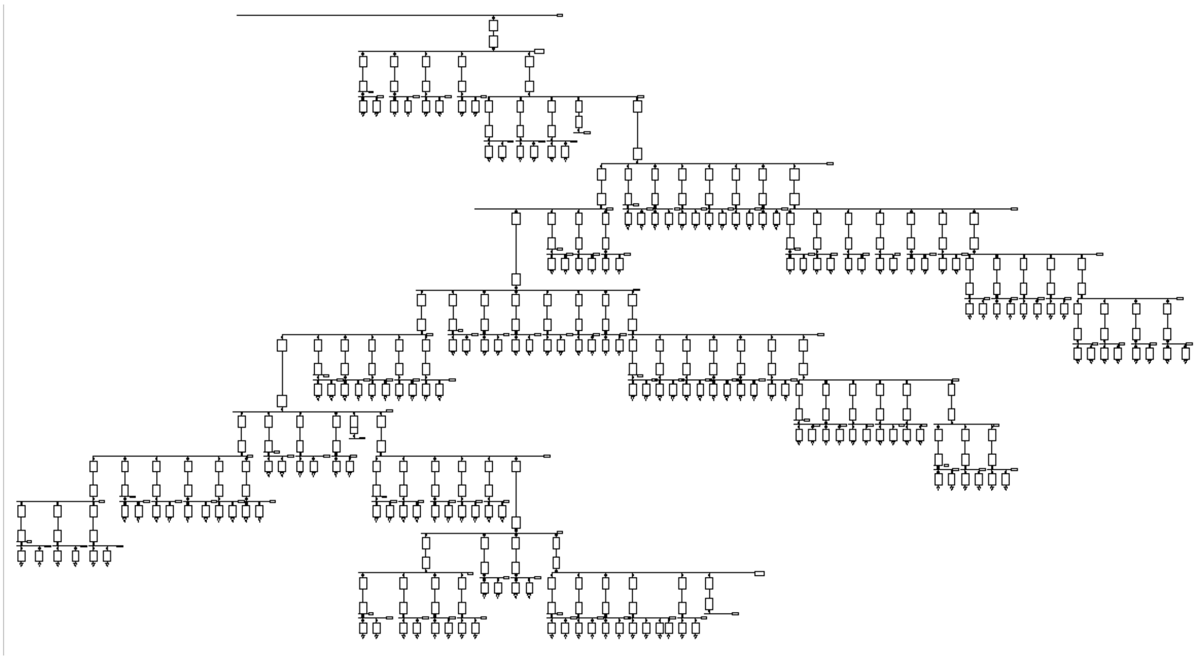


Figure F.8: Feeder 44005