POLITECNICO DI TORINO

Corso di studi in Ingegneria Elettrica

Master of Science Thesis

Optimal aggregation of electric cars for their charging within smart distribution grids

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Preface

This thesis is mainly based on a study conducted at the Department of Energy Technology, Aalborg University, during the period 2nd of February to the 30th of May 2016. Afterwards it has been revised and extended, through a questionnaire and a local analysis, to a case study at the Politecnico di Torino.

The main objective is to develop an optimal aggregation of the EVs in the Danish power systems with the aim to test the performance of the grid when dealing with integration of EVs and develop efficient algorithms for their smart charging, considering the grid constraints and the operating limits. Also, to analyze the feasibility of the EV integration and evaluate the installation of charging columns inside the Politecnico.

I am grateful to my family and dear persons who believed and supported me during these years, which made it easier to achieve this goal.
I want to thank Prof. Jayakrishnan Pillai & Prof. Sanjay K. Chaudhary at Aalborg University and also Prof. Bruno Dalla Chiara & Prof. Gianfranco Chicco at PoliTO for their constant guidance throughout the course of the thesis.

Nomenclature

BEV	Battery electric vehicle
CHP	Combined Heat and Power
CO_2	Carbon dioxide
DER	Distributed energy resource
DKK	Danish Krone
DOD	Depth-of-discharge
DR	Demand response
DSO	Distribution system operator
ELSPOT	Nord pool spot’s day-ahead auction market
EV	Electric vehicle
EVSE	Electric Vehicle Supply Equipment
GPS	Global Positioning System
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
PHEV	Plug-in hybrid electric vehicle
PM	Particulate Matter
PM2.5	Small particles less than 2.5 micrometers in diameter
PV	Photovoltaic
RE	Renewable energy
SOC	State of charge
TSO	Transmission system operator
V2G	Vehicle-to-grid

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1 Introduction

A new report from the Global Sustainability Institute warns that many countries of the European Union are facing severe critical shortages of fossil fuels and other natural resources in the near future [1].
Denmark has always promoted the use of renewable energy and is one of the pioneers in producing electricity from renewables like wind power. Its objective is to be fossil-fuel independent by 2050 [2]. With more penetration of intermittent renewable energy like wind power, the system operation will be more complex and it will require additional balancing power.
Electric vehicles could support the penetration of wind power with a proper communication and control infrastructure. When coupled to an electricity network they can act as a controllable load and energy storage (V2G technology) in power systems with high penetration of renewable energy sources [3].

1.1 Background and motivation

The energy crisis has been an important issue for the last few decades. The shortage of fossil fuels is now a reality and it is estimated that oil reserves left on the planet will run out on the next 50 years [4]. Their impact on the environment is becoming every day more serious.
The European Commission for Climate Change has concluded, after analyzing studies from different institutions, that automobiles are responsible for around 12% of total EU emissions of carbon dioxide (CO2), the main greenhouse gas. This leads to an ecosystem disorder, and the level of PM2.5 (small particles less than 2.5 µm in diameter) is becoming every day more alarming [5].

In Denmark, the most important renewable energy source is the wind power. It is an inexhaustible energy with zero CO_2 emission, environment friendly and has a matured technology. Denmark has been committed to develop wind power for decades, where nowadays more than 39% of electricity consumption is covered by wind generation, against only 2% from 1990 (Figure 1-1) [6].

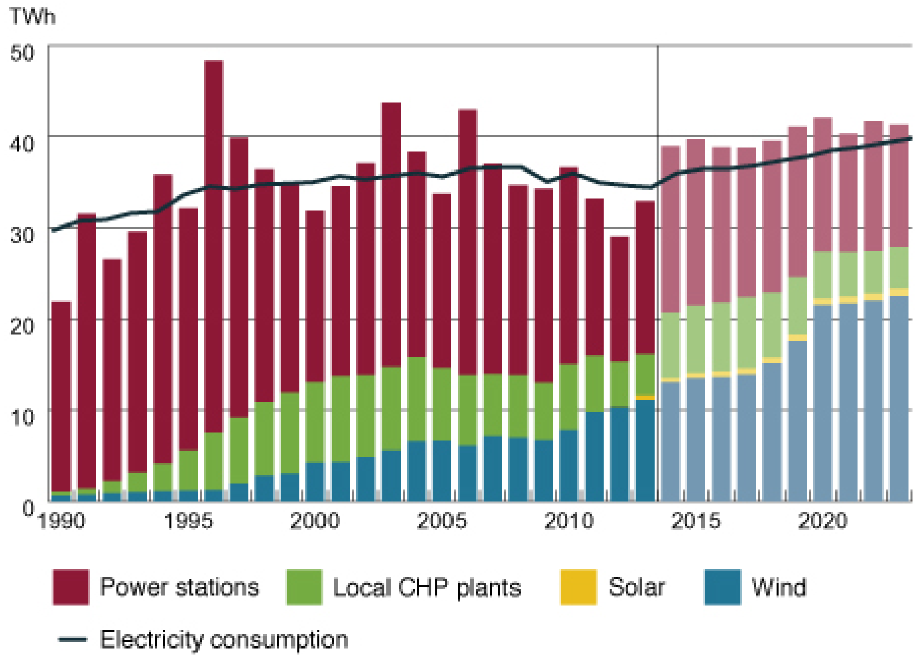


Figure 1-1 Electricity consumption and generation in Denmark [6]

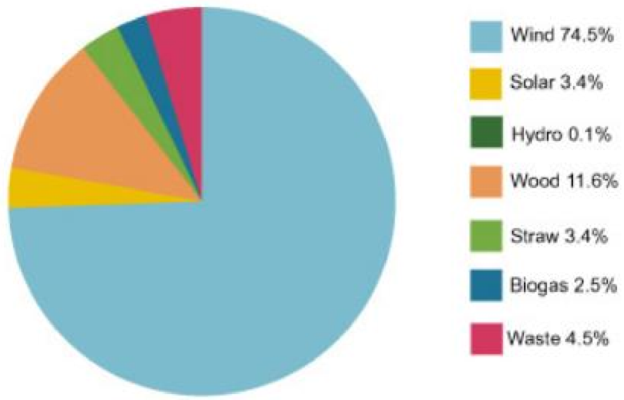


Figure 1-2 Percentage distribution of RE-based electricity generation in Denmark [6]

Figure 1-2 shows the distribution of renewable energy (RE) based power generation in Denmark in 2014, dominated by wind power which constituted 57.4 % of the total electricity generated.
The new initiatives of the government are planning to cover 50% of the electricity demand by wind power until 2020 and to make a complete phase-out of coal by 2030. The goal is to be independent of fossil fuels by 2050 [2].

The electric vehicles have been put on the energy agenda to replace the gasoline vehicles in the future. The price of gasoline in Denmark is much higher than in the US and the tax for buying a gasoline car is also very high, while there is low or no tax for EVs [7]. Also, the EV batteries can act as energy storages to support the power system with high wind penetration.

Since the wind power is hard to forecast and it causes some reliability and stability issues in the grid, EVs can support such system as a new load but also as a renewable energy resource (acting like generators with the V2G technique) [3].

As sizeable loads, charging EVs can easily affect the distribution grid. The voltage drop and the grid losses will increase considerably. The plans for promoting EVs should be made by considering the capacity of existing grid and future smart grids involving information and communication technology.

1.2 Objectives

- The main objective of the thesis is to develop an optimal aggregation of the EVs in the Danish power system, in an always increasing demand of energy consumption and penetration of renewable energy sources, mainly by wind power.

- The thesis aims to test the performance of the grid when dealing with integration of EVs and develop efficient plans for their smart charging, considering the grid constraints and the operating limits.

- To make the integration more feasible and convenient, while keeping the stable operation of the grid, some economic charging plans are aimed to be made, to optimize the charging cost so both aggregators and consumers can benefit.

1.3 Methodology

- The thesis is based on the Danish power system, so initially the issues with high wind penetration are analysed. To better understand the impact of wind power in the power systems, it is essential to know also how the electricity market works in Denmark.

- The concept of EVs will be explained and also their battery characteristics. The driving patterns are included to better predict the behavior of the EV owners and understand their charging needs.

- For the charging of EVs some base cases will be implemented depending on the season and weekday/weekend. Initally the grid robustness will be tested, then dumb charging of EVs is analyzed. To make the study realistic, the annual household consumption data, the driving patterns and the available charging times will be used to generate random behaviour of the EVs in different scenarios.

- In order to promote the spread of EVs and have a stable grid operation, smart charging will be implemented. With the optimization of the charging cost it can be concluded how much it can benefit the grid operation and the consumers.

- The load flow will be analyzed with DigSILENT tool, using the Newton Raphson method as the base method to calculate it. On the other hand, Matlab will be used to simulate the optimization of the charging and also the optimization of the V2G concept.

1.4 Limitations

- In this thesis the study is limited to a small residential distribution grid and EVs will be charged only at home, after the owners come back from work.

- The smart charging is based on the Elspot Market price

- There will not be considered any kind of voltage fluctuations, voltage dip, flicker, generation of harmonics and various other power imbalances in the grid.

- The various information and communication technologies will not be analyzed. It is assumed that we deal with a balanced three-phase system, so no dynamic studies are involved.

- The study will be focused only on pure battery electric vehicles (BEVs)

- The operation of the power system in the future cannot be completely predicted. The type of EVs considered in this project may not necessarily represent the EVs in the future.

1.5 Outline of the thesis

This part of the report presents a brief explanation of each chapter:

- Chapter 2 describes the state of art of this topic: the background of the electric vehicles, the issues regarding the wind power penetration in Denmark and the energy market. An architecture of different types of charging is implemented and also V2G technology concept is explained.

- In Chapter 3, the driving patterns, available charging times and the consumption of EVs are analysed to generate random data for charging the EVs.

- Chapter 4 consists in the analysis of the distribution grid. The performance of the grid is tested and its ability to deal with EVs in dumb charging mode in different scenarios. The purpose is to see how many EVs can be integrated and which are the limitations of the grid. DigSilent Powerfactory is used for the simulation.

- In Chapter 5, the smart charging is implemented based on the electricity price variation, which depends on the fluctuating wind power. Moreover, a comparison between the cost of dumb and smart charging is done, and also the revenues of the EVs in participating in V2G are shown. Matlab is used for the generation of the stochastic data and the cost optimization.

- Chapter 6 consists on the survey conducted at PoliTo about the transition of the staff's ICE cars to EV/HEV. The data provided by the users is processed and a final result about the convenience on switching to an EV/HEV is given. Also some evaluations on installing charging spots inside the university are done, including 2 scenarios with uncontrolled and controlled charging

- The conclusions and the possible future work are presented in the next sections

2 EVs in the distribution grid

2.1 Issues with high wind power penetration

The targets for Denmark regarding the wind power penetration are to increase the energy production from wind power from 25% to 50% of the electricity demand by 2020 and to make the energy production independent of fossil fuels by 2050. At present, the wind power production in Denmark is approximately 25% of the energy request [8].
In 2014, Denmark had 4855 MW installed wind capacity of onshore turbines and 1271 MW from offshore turbines [9].

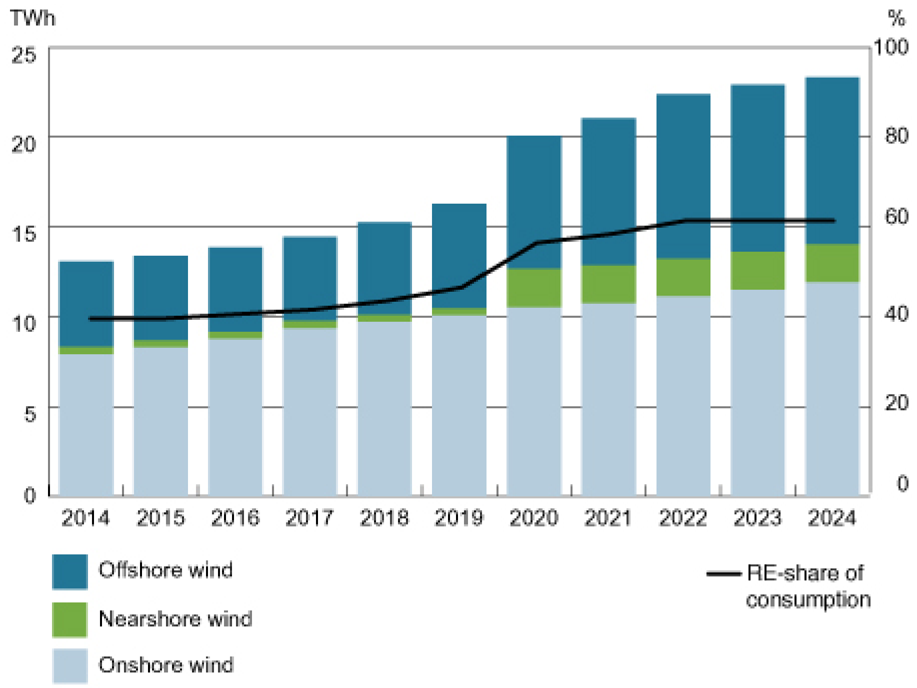


Figure 2-1 Electricity generation from wind turbines until 2024 in Denmark [10]

Figure 2-1 shows the predicted wind power generation in Denmark towards 2024. The total production from offshore, nearshore and onshore wind turbines is assumed to be 23.3 TWh in 2024 approximately 61 % of the electricity demand.
One of the most important issues of wind power is the incapability of ensuring generation to the transmission line without interruption [11].

During periods in which the wind is high, the generation through wind power also increases. This means that the production is also greater than the consumption and, consequently, the cost of electricity is lower. Conversely, when the wind is low there is not much generation of energy through the wind turbines. In this case since the generation is lower than the demand or consumption the cost of electric energy generated is higher.

The extra energy generated should be exported to the neighboring countries [12]. Figure 2-2 shows the wind power generation in Denmark on the 9th of July 2015.

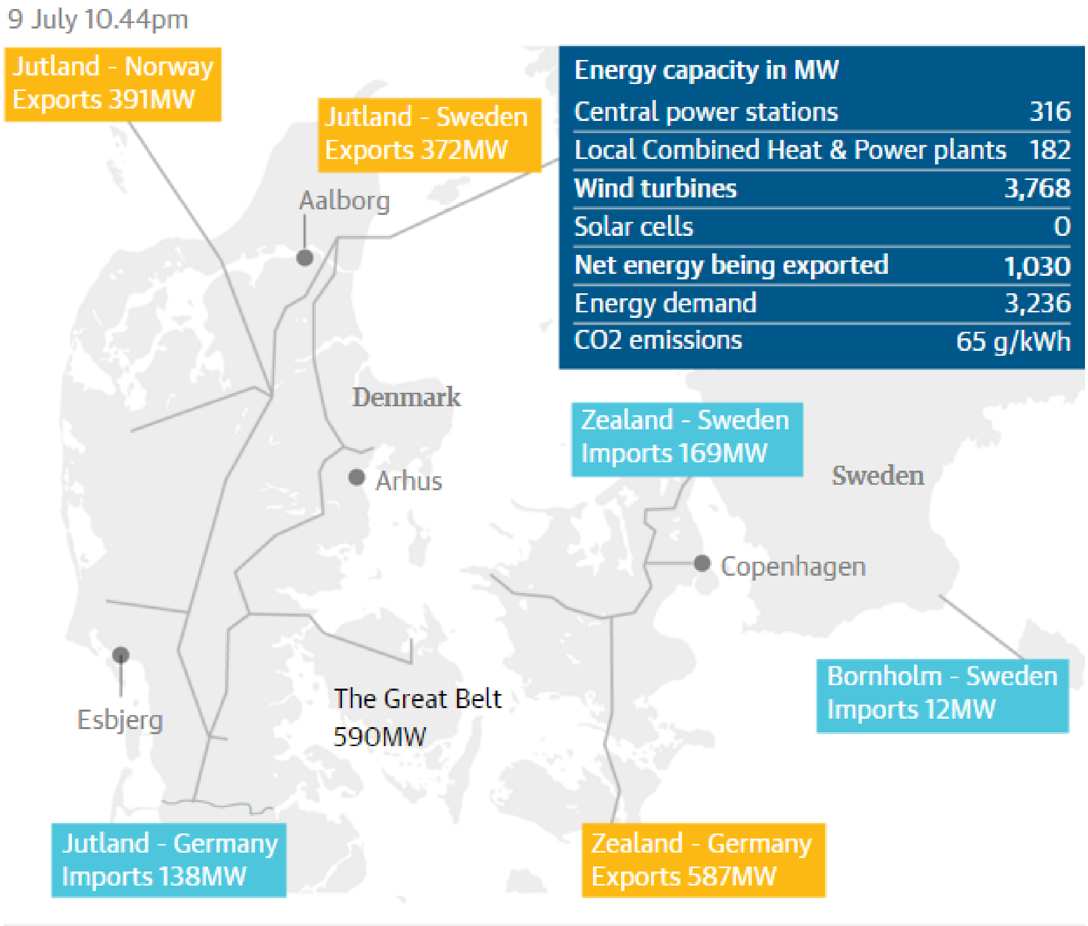


Figure 2-2 Power System in Denmark. Wind power generation on 9th of July 2015 [10]

The large scale penetration of wind power into the existing grid results in various challenges for transmission system operators. The production of reliable electricity involves maintaining proper balance between the generation and consumption. Since the nature of the wind cannot be predicted accurately, the power generated from wind decreases the overall demand. However, the integration of large scale penetration of wind power requires proper planning due to the intermittent nature of the wind. Fluctuations in wind power are mainly caused by changes in the weather patterns [13].

The concern about the power quality issues has appeared after the installation of the two offshore wind farms in Denmark, the 160 MW Horns Rev wind farm and 165 MW Nysted wind farm. This is due to the impact they caused on the transmission system [14]. At the Horns Rev offshore plant, the wind power variations were recorded for every fifteen minutes and it is found that for 50 % of the time the wind power does not vary. With an increasing number of wind farms, the fluctuation in the demand may become an issue. The onshore farm in Horn Rev consists of 80 turbines generating about 160 MW around 20 km^2 experienced power fluctuations about 100 MW in 5 minutes [13].

On the distribution system, the first issue is the voltage in the grid, which needs to be kept within an admissible limit [14]. In the European voltage standard [15], it is tolerable ±10 % of the average voltages during 10 minutes at the final users that can secure the well functioning of the appliances. The methods used to control the voltage fluctuation are the limitation of the inrush currents to limit voltage drops, and the flicker analysis.

These methods are studied based on the measurements on the 33 kV grid in the Nysted (DK) offshore wind farm. If the voltage drops, the wind turbines must have the capacity to stay connected, otherwise a notable production capacity can be lost [14].
In a balanced system, huge variations in power can cause a lot of problems if proper forecasting of wind is not done accurately. For a proper operation of a power system where there is huge penetration of wind power, wind forecasting plays a pivotal role for proper system operation.

2.2 Background of EVs

As explained, the avoidance of fossil fuels will affect, among other aspects, the way people move around places. And this will involve an increasing usage of Electric Vehicles.
The aim of this section is to give an overview about the history and technologies around the concept of the Electric Vehicle.

2.2.1 History and types

Electric vehicles are those that are powered by an electric motor instead of a gasoline engine. The group formed by electric vehicles can range from electric trains, buses or even boats, to electric cars, which are the major known.

The first electric vehicles, which were used in the 1830s, didn’t use rechargeable batteries. By the end of the 19th century, electric vehicles started to be sold on the market and become widely used. This was possible due to the mass production of rechargeable batteries [16]. However, the popularity of electric cars didn’t last for long. This was due to many reasons such as the discovery of crude oil, which became cheap and was available in rural areas (whereas electricity was not available everywhere) and the introduction of electric starters. So by the 1920s the electric cars entered a sort of dark ages caused by the lower prices of gasoline cars [17].

Some years later, around the 1990s, electric vehicles became commercial again in the States and around the world thanks to some regulations about transportation emissions [17].

Electric vehicles are commonly divided into Battery (BEV), Hybrid (HEV) and Plug in Hybrid Electric Vehicle (PHEV).

Battery electric vehicles are those that are powered only by an electric motor instead of a combustion engine. The vehicle consists of a battery as the energy storage device, an electric motor and controlling system . EV's batteries must be replenished by plugging in the vehicle to a power source. Some of them have on-board chargers, but there are others that are plugged into a charger located outside the vehicle [16].

Hybrid electric vehicles can be divided into three main groups: the series hybrid electric vehicle, the parallel hybrid and the one which combines both. These common types combine an internal combustion engine (ICE) with a battery and an electric motor and generator. This kind of EV does not have a plug in order to charge batteries, it uses the regenerative braking technology instead [16].

PHEVs work similarly to conventional HEVs, but they have larger batteries. That means that they can be plugged from the mains to charge [18].
There are several PHEV cars that were put on the market some years ago and they are still being sold nowadays with big success. Some of the models in the market are Toyota Prius and the Mitsubishi Outlander [19].

2.2.2 Advantages and limitations

There are several opinions regarding the use of electric cars. In this section some of the advantages and disadvantages are explained.

The main advantage of an electric vehicle over the gasoline one is related to environmental issues. Although electricity production may contribute to air pollution, EVs are considered zero emission vehicles because their motors do not produce exhaust gases or emissions. That is also linked to the fact that there is no gas required, so they are more economical from the fuel cost perspective. Also, in some countries, it is possible to receive money from the government for using this type of vehicles. This is the case of the government from the UK that gives a grant towards a new electric car if it accomplishes certain conditions [20]. In Copenhagen, for example, it is allowed to park EVs for free around the city [21].
Another benefit is that electric cars run on electrically powered engines and hence there is no need to lubricate the engines. Therefore, the maintenance cost of these cars is lower [22].

There are also some disadvantages. Regarding the charging points for EVs, there is still a gap. Not a lot of places have charging stations, which means that in case of a long trip, it may be difficult to charge the car in all routes. Furthermore, it takes a long time to charge them with "normal" charging power (6-8 hours) while it only takes few minutes to fuel a gasoline car [23] .
The last limitation is related to the life cycle of the batteries. Depending on the type and usage of battery, it has been proved that batteries require to be changed for a maximum of 10 years [24] [25]. That's why most companies rent the battery of their vehicles instead of buying it.

As it can be seen in Figure 2-3, the costs of having non-electric vehicles differ from the ones that are still using fossil fuels. This demonstrates that it is important to consider the possibility of buying an electric car instead of a fossil fuel one even if the initial cost is higher.

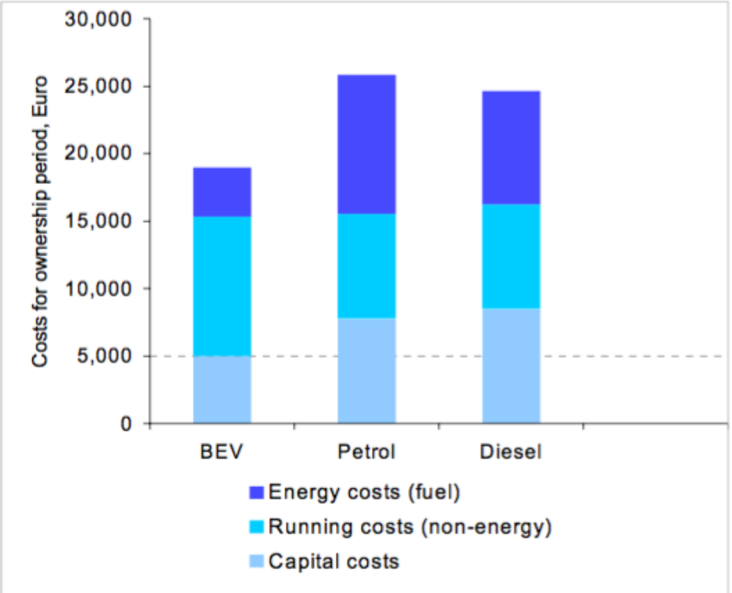


Figure 2-3 Comparison of the relative costs of ownership of battery electric cars compared to petrol and diesel equivalents [8]

2.2.3 Batteries of EVs

There are many types and sizes of batteries. It is very important to consider their weight and volume due to the limited space in the vehicles to fit them.

A battery consists of many cells connected together that convert chemical energy to electrical energy. Every cell has positive and negative electrodes in an electrolyte and their chemical reaction generates DC electricity.

In Table 2-1 some of the main batteries that have been used in EVs are shown.

Table 2-1 Batteries used in electric vehicles of selected car manufacturers [16].

Company	Country	Vehicle model	Battery technology
GM	USA	Chevy-Volt	Li-ion
		Saturn Vue Hybrid	NiMH
Ford	USA	Escape, Fusion, MKZ HEV	NiMH
		Escape PHEV	Li-ion
Toyota	Japan	Prius, Lexus	NiMH
Honda	Japan	Civic, Insight	NiMH
Hyundai	South Korea	Sonata	Lithium polymer
Chrysler	USA	Chrysler 200C EV	Li-ion
BMW	Germany	X6	NiMH
		Mini E (2012)	Li-ion
BYD	China	E6	Li-ion
Daimler Benz	Germany	ML450, S400	NiMH
		Smart EV (2010)	Li-ion
Mitsubishi	Japan	iMiEV (2010)	Li-ion
Nissan	Japan	Altima	NiMH
		Leaf EV (2010)	Li-ion
Tesla	USA	Roadster (2009)	Li-ion
Think	Norway	Think EV	Li-ion, Sodium/Metal Chloride

2.2.4 State of Charge (SOC) of the battery

As for a single EV, the state of charge of its battery depends on how long the car has been driven. Then the SOC determines the charging duration the EV needs. To determine the Depth Of Discharge of a battery,the following equation is used, where it is subtracted the remaining capacity of the battery from the maximum.

$$DOD = 1 - SOC \quad (1)$$

Where:

DOD is the Depth Of Discharge
SOC is the State of Charge

2.2.5 EV chargers and charging/discharging technologies

The time spent to charge the battery and also the battery life are connected to the characteristics of the battery charger. This must be efficient and reliable, with high power density, low cost, and low volume and weight [23].
Chargers can be split up into on-board and off-board with unidirectional or bidirectional power flow. In general, on board chargers limit high voltage because of weight, space and cost constraints and they can be conductive or inductive [23]. Conversely, off-board chargers can operate at high charging rates and they don’t have many constraints regarding size and weight.

The term of unidirectional charger is used when they can charge the vehicle, but they are not able to inject energy into the grid. The bidirectional chargers can both receive and inject power back to the grid.

2.2.6 Charger power levels

Charger power levels reflect power, the duration of the charging, the charging location, cost, equipment and effect on the grid. The rollout of what is known as the Electric Vehicle Supply Equipment (EVSE) has to be really considerate for many reasons such as charging time, distribution, extend demand policies, standardization of charging stations and also regulatory procedures [23].
Some of this equipment includes the charge cords, charge stands, attachment plugs and vehicle connectors. These components are normally found in two configurations that are a special cord set and a wall or pedestal mounted box. Depending on the location or even the country, there can be some differences regarding the different configurations of plugging the vehicles.

The power levels are divided into three different levels that are the followings:

- Level 1 is the slowest method. As shown in the table below, it uses a standard 120V/15A or 230V/10A (Schuko) single-phase grounded outlet. The connection may use a standard J1772 connector into the EV AC port [26].

- Level 2 is the primary method for dedicated private and public facilities. Contrary to level 1, this level may require special equipment and a connection installation for home or public units. Owners usually prefer this level due to the reduced time to charge the vehicle and also due to the standardized vehicle-to-charge connection [26].

- Level 3 is known as the commercial fast charging. It offers the possibility of charging within one hour. It can also be installed in highway rest areas and city refuelling stations. The connection to the vehicle may be direct DC [26].

Table 2-2 Overview of the different charging power levels [26]

Level	Charger location	Typical use	Energy sypply interface	Power level
Level 1 (Opportunity. 120V/230V)	On-board 1-phase	Home or office	Convenience outlet	Up to 2.2 kW
Level 2 (Primary. 240V/400V)	On-board 1 or 3 phases	Dedicated outlets	Dedicated outlet	4-20 kW
Level 3 (Fast. 480V/600V or direct DC)	Off- board 3-phase	Commercial filling station	Dedicated EVSE	50-100 kW

2.2.7 Fast charging vs. slow charging

Slow charging is normally associated with overnight charging, which is translated into a 6-8 hour period. This method makes use of the EV on-board charger. Fast charging could be defined as any other scheme that doesn't include slow charging. Even though, the term of fast charging could be divided into the following classification [27].

Table 2-3 Power levels for DC charging [27]

Type of Charge	Charger Power Level. kW		
	Heavy Duty	SUV/Sedan	Small Sedan
Fast Charge. 10 minutes. 100% SOC	500	250	125
Rapid Charge. 15 minutes. 60% SOC	250	125	60
Quick Charge. 60 minutes. 70% SOC	75	35	20
Plug-In Hybrid. 30 minutes	40	20	10

2.2.8 EVs in Denmark

In Denmark, as in many other countries, EVs are taking an important role in the sustainable transport. In the 2012 there was an important Energy Agreement in Denmark in which were discussed very ambitious initiatives that try to get closer to the target of 100% renewable energy, in the energy and transport sectors by 2050. Nowadays the Danish transport is mostly run on combustion vehicles. However, there are several plans to promote the green transition in the transport sector. For example, there will be an investment of DKK 70 million to establish more recharging stations for electric cars. Also, DKK 15 million will be used to keep the pilot scheme for electric cars going on [28].

Also, taking into consideration that by 2020 approximately 50% of electricity consumption will be supplied by wind power, it's cost will decrease when the wind speed is high [28]. Additionally, if consumers enrol in some of the existing Demand-Response (DR) programs, then charging an EV for a reasonable price won't be an obstacle for them.
The DR consists on the electricity consuming changes done by the end-use customers in response to changes in the price of electricity overtime [29]. There are different actions that can be carried out by customers in order to reduce the cost of the electricity bill. Some of them, such as to charge the EV during off peak demand periods, can make a positive impact by reducing the electricity bill.

2.3 Electricity market in Denmark

Electricity market basically works as any other market. Each type of market is composed of producers, retailers and also the users. However, for the electricity market the trading system is more complex than others. This means that from the usual 'players', there are two more people that enter into the market. These are the traders and the brokers (Figure 2-4).

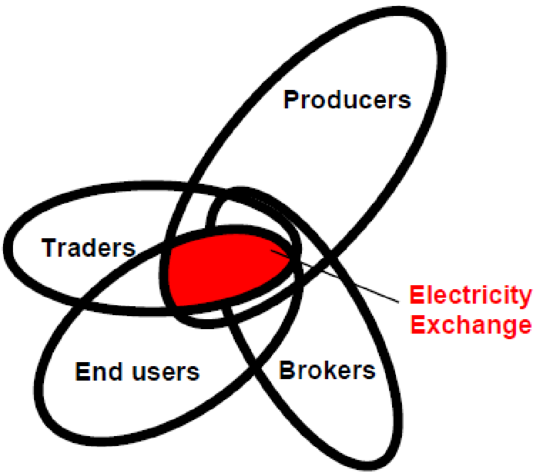


Figure 2-4 The commercial players and the electricity exchange [30]

In the next few lines, each role of these players will be explained.

- Traders are the players who own the electricity during a trading process. They may buy electricity from producers who produce at low prices and sell it to a retailer. Or the same process may occur, but buying from a retailer and sell it to another retailer.
- Brokers are the intermediary of the process, exactly like in estate market.
- Retailers use the help of the brokers to find a producer that will sell a specific amount of energy in a given time [30].

An example of an electricity market is the Nord Pool Spot exchange, which includes countries such as Denmark, Finland, Sweden, Norway and Estonia.

2.3.1 The transmission system operator (TSO)

Regarding safety issues of the market, the transmission system operator (TSO) is responsible. The TSO controls the electricity and makes the rules in order to do the necessary changes in a safe way, keeping the frequency at 50 Hz.
In Denmark, the TSO is the state-owned grid company called Energinet.dk and it manages both electricity and gas.

2.3.2 Regulating power market

As mentioned before, the TSO has the responsibility to make the system stable. For this to happen it has to balance the production with consumption, which most of the time are not equal. When this happens, the frequency of the alternating current falls to a value below 50 Hz if the consumption is more than the production, and exceeds 50Hz viceversa. When for example the consumption is greater than the production, the TSO must ensure that one or more producers deliver more electricity to the grid (Figure 2-5). In this case, the TSO buys more electrical power from the producers that have excess generation capacity. The term for this measure is “up regulation”.
Contrary, if production exceeds consumption, producers have to lower their production. This is known as “down regulation”.

2.3.3 Balancing Power

The transactions made in electricity market are made hourly. In Figure 2-5 there is an example where a retailer buys electricity for one particular hour at a specific date. This hour, when the transaction is made, is called the hour of operation.

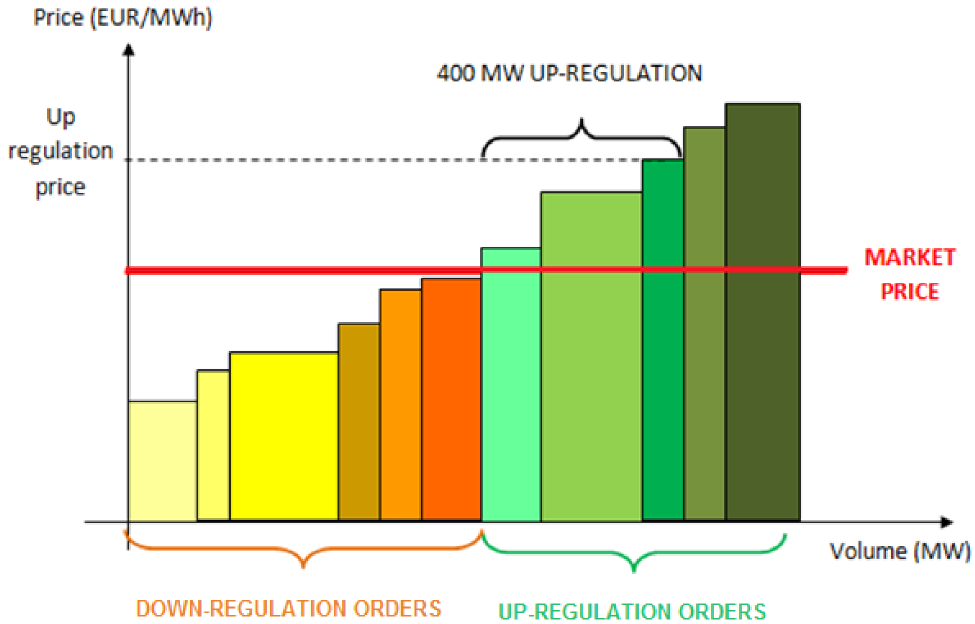


Figure 2-5 Price setting in the regulating power market [30]

2.3.4 Elspot – Nord Pool Spot's Day-ahead Auction Market

Elspot is Nord Pool Spot's day-ahead auction market, where electrical power is traded.
Players, who want to trade power on the Elspot market, must send their purchase orders to Nord Pool Spot at the latest at noon the day before the power is delivered to the grid.
At Nord Pool Spot, the purchase orders are aggregated to a demand curve. The sale offers are aggregated to a supply curve. The intersection of the two curves gives the market price for one specific hour.
Regarding the Danish production and demand curve, local CHP production and wind power production, which is the main source of energy for Denmark, have low marginal cost due to feed-in tariffs [30]. This fact leads to a drop in the spot price, when the wind production is high. An example of production and demand curves is presented in Figure 2-6.

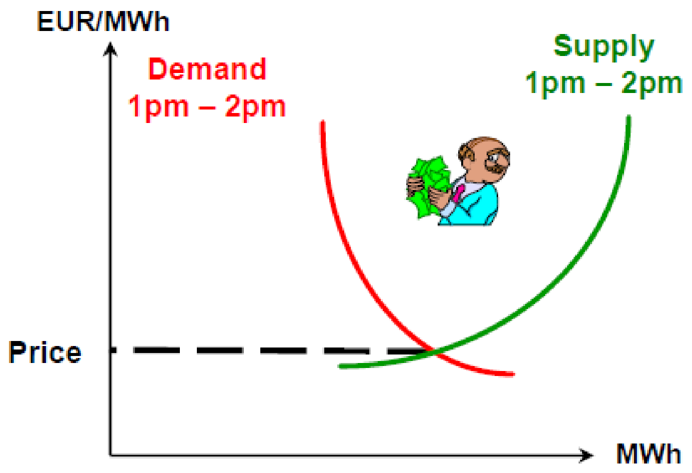


Figure 2-6 Supply Demand per one day [30]

Nord Pool Spot calculates a price per each hour. Elspot is a day-ahead market, as this is trader for the following day. This way of calculating the price is called a double auction, as both the buyers and the sellers have submitted orders. Hence, Elspot is called a day-ahead auction market.

From this, it can be concluded that consumers may be determined to consume more when there is an excess of electricity. By this they will help the TSO and the safety of the grid.

2.3.5 Elbas Market

After the market closes, a lot of changes in production or consumption may occur. These consist of improved wind speeds, or failures and outages. For this, another market is needed, and it is called intraday or Elbas market, which differ to the Elspot market, and closes one hour before operation [30].

2.4 Architecture of the EV charging

Electric consumption is increasing everyday and it is expected that large-scale penetration of EVs will increase it significantly. Though, power flows, grid losses and voltage profile patterns along the grid will change considerably. In order to manage such increase of electricity demand, Denmark is promoting the Smart Grid (Figure 2-7).

Its objective is to make the grid more intelligent. This means to have a better communication with all parts of the system, in order to integrate more wind power and more EVs.
This would reduce the stress in the distribution grids, and the electricity consumption would be more flexible and economical. Consumers could participate in the regulating market, for example, charging EVs in late evening, when the price of electricity is cheap [31].

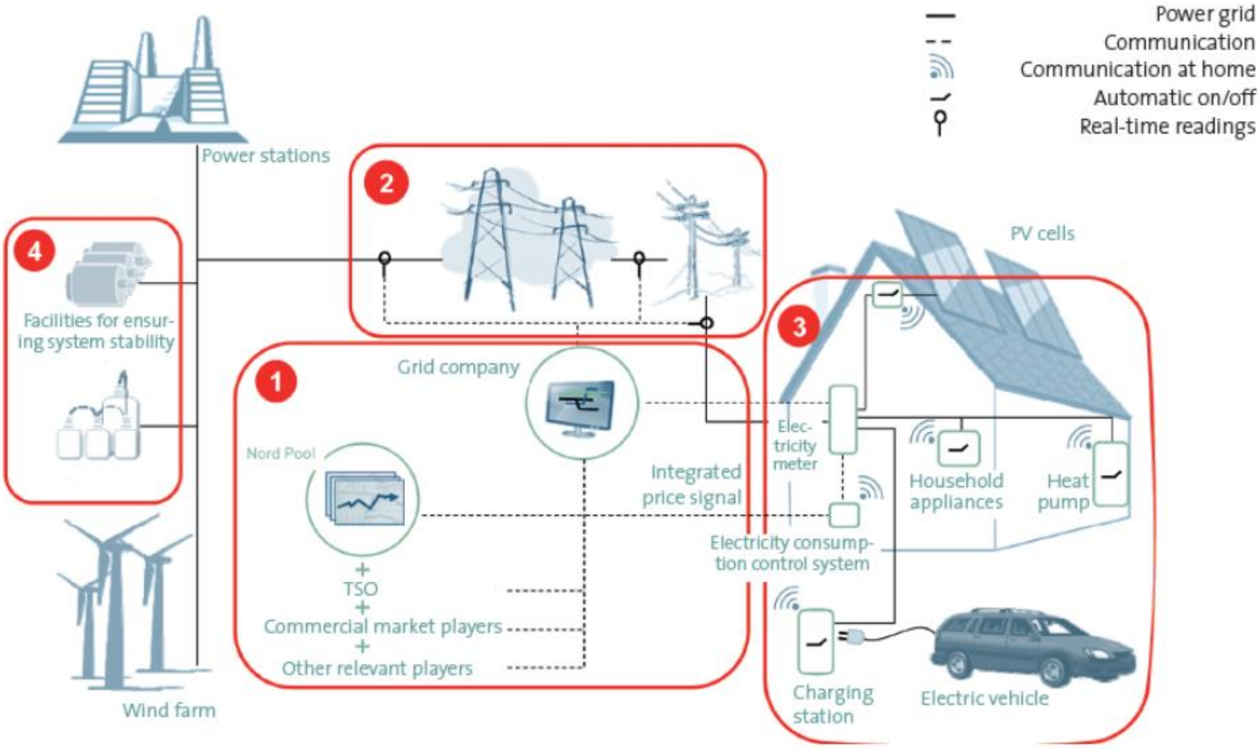


Figure 2-7 Smart grid in Denmark proposed by Energinet.dk [31]

Table 2-4 shows the changes that the grid is facing and how they could be solved by implementing the Smart Grid.

Table 2-4. Overview of the actual changes and possible solutions [32].

	What is changing?	Possible solutions
Low voltage distribution grid	A smaller renewable generation is being connected to the grid, creating two-way flows in a network that was only designed for one-way flows. Consumers are installing renewable generation, such as solar panels, for their own consumption. There is a higher demand since there are more people who have EVs. That means that the peak of demand increases in terms of power and also in its duration. Water heating could be converted from gas to electricity in the next 15 years, so the demand will also increase even more in winter. Distribution companies need to ensure that the grid is not overloaded and the quality is maintained.	In order to control the two-way power flows it will be necessary: To install Smart meters in each household to pay customers for the electricity they produce. These devices will also help in the design of the network. To manage the demand by creating different shifts and reward customers who adapt their consumptions to these plans. Trying to maintain the same quality it will be necessary to focus on the efficiency of the grid. This involves the use of more automation and intelligent systems.

The main concerns that have to be controlled in a smart grid are:

- Frequency, which is controlled by matching generation and demand. By doing this, it can be ensured that every customer will receive electricity at a constant frequency [32].
- Voltage, which is controlled by the usage of generators and transformers.
- Current that has to be maintained in certain levels in order not to exceed the upper limit of the grid's devices. This is done by providing spare capacity in the grid together with control and protection actions[32].

Next, the two possible EV charging scenarios which will be implemented will be explained.

2.4.1 Dumb charging

The 'plug and charge' is referred to dumb charging, which means that EV owners can plug their vehicles whenever they want, without any kind of charging control performed by the aggregator [33]. Generally this happens when they get home in the afternoon/evening.

EVs are connected to the grid by the usage of a conventional outlet or a charging post. Once the vehicle is connected, the charging will start automatically and it will proceed until the battery is fully charged [33].

Nowadays most people charge their EVs in dumb charging mode. This doesn't help the grid, since it is more difficult to predict the consumption from the different households. And as a result, the grid has to face with numerous stability problems.
Also it might be convenient for the consumers to charge at midnight when the electricity price is lower.

In this thesis, the dumb charging has been applied in order to see the maximum number of EV's that could be safely charged without damaging the grid. This simulation will be shown in chapter 4 (Base case analysis).

2.4.2 The smart charging

Smart charging of an EV is when the charging cycle is changed by external events, such as the fluctuation of the wind which can imply a higher or a lower price for the electricity. The charging is controlled and monitored by the aggregators. They make a plan to decide the charging time and power, while the consumers plug in their EVs when they get home. The aggregators will guarantee the stability of the grid, try to minimize the cost and make sure that EVs are charged to fulfil the consumers' requirements before the next morning.

To manage a large-scale deployment of EVs while charging, the power system will require a combination of:

- a centralized hierarchical management and control structure
- a local control located at the EV grid interface

The efficient operation of the system will depend from the combination of local and centralized control. This control approach is based on the creation of a proper communications infrastructure which will be able to handle all the information exchanged between the control structure and the EV.

When the grid operation is in normal conditions, the aggregator will manage and control the EVs, which function will be to group EVs to participate in the electricity markets, according to their owners' willingness.

The consumers will have contracts with the aggregator, which will develop strategies of charging to minimize the cost, stabilize the grid and support the wind power production.
Based on historical data, the aggregators will forecast the market behavior for the next day and prepare their buy/sell bids. Of course, everything has to be approved from the DSO first, to avoid grid problems [3]. An architecture of the charging is proposed in Figure 2-8.

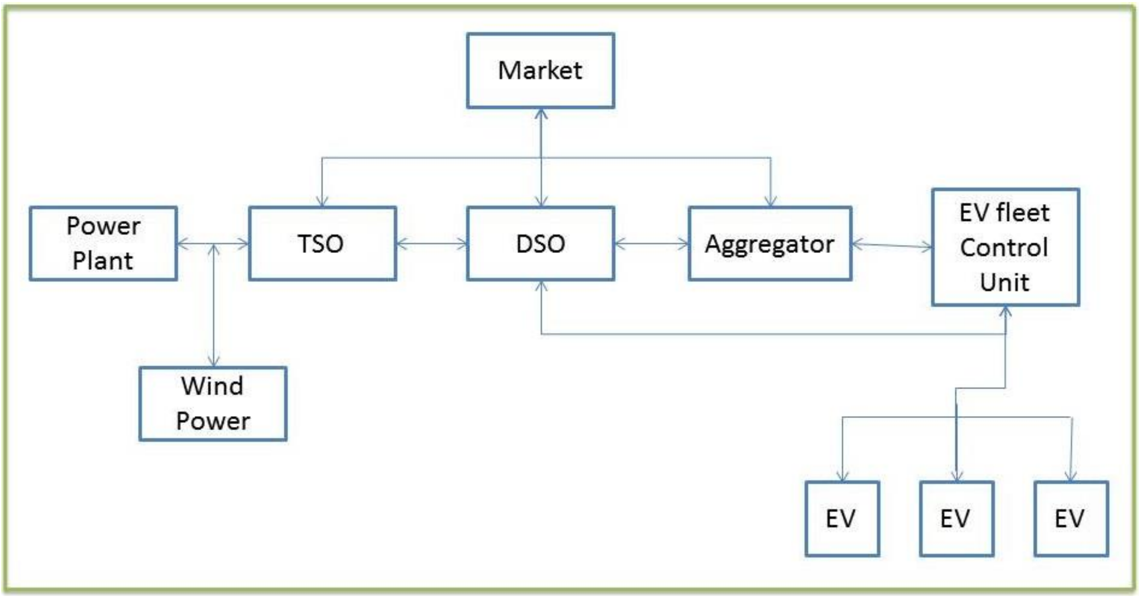


Figure 2-8 Proposed architecture of the EV charging

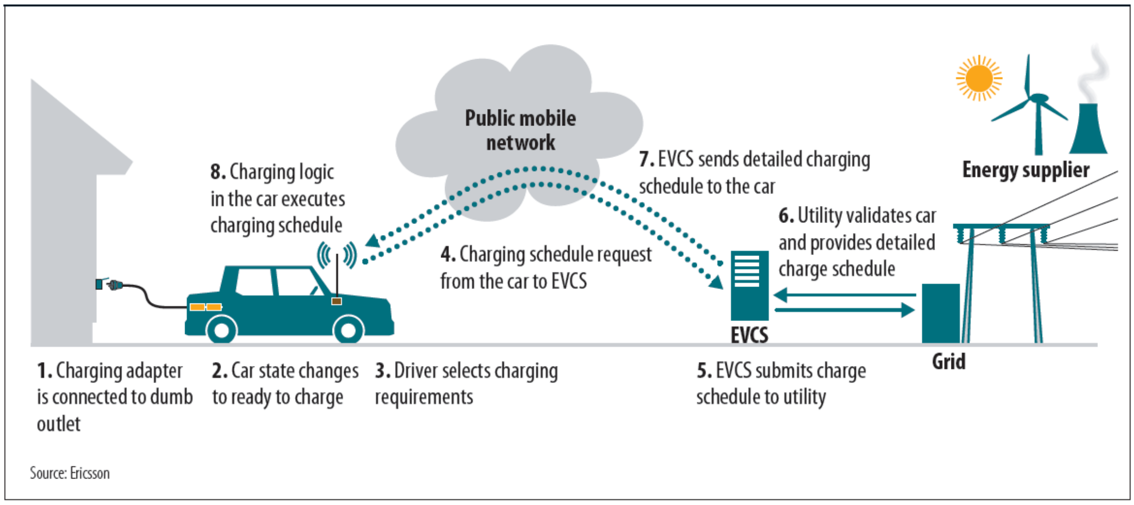


Figure 2-9 Example of the smart charging system [34]

However, in abnormal operating conditions, a grid monitoring structure is required, managed by the Distribution System Operator (DSO), which will also influence the charging of EVs.
In these circumstances, EVs might receive simultaneously two different set points: one of the monitoring and management structure, controlled by the DSO, and another from the aggregator. The DSO has the priority over the aggregator, to avoid violation of grid operational limits. In this thesis, smart charging simulation is done in chapter 5 (Simulation of smart charging in winter weekday).

2.5 Vehicle-to-grid (V2G) technology

Renewable energy systems are characterized by a variable input, and it is estimated that for every 10% of wind penetration, 2-4% of balancing power from other sources is needed, for a stable system operation [35].
A large scale penetration of intermittent renewable energy will make the system operation more complex and more balancing power will be required. To avoid the use of conventional generators, some storage technologies could be used. V2G can store energy when there's low demand and supply it when high power is needed. The EV owners could also have a considerable annual benefit by participating in V2G.

V2G technology could use the storage of the battery electric vehicles and their quick response to deal with the fluctuating power produced by renewable energy. The batteries can act either as a load or energy source, depending on the system operation. The electricity supplied from V2G will reach the consumers through the grid connection, while if there is a surplus energy in the grid it will be stored in the electric vehicles. The TSO decides whether calling a single or a fleet of EVs for power transfer through a control signal based on internet connection, mobile phone network or a power line carrier [36].

In Figure 2-10 it is shown the V2G scheme along with its main components.

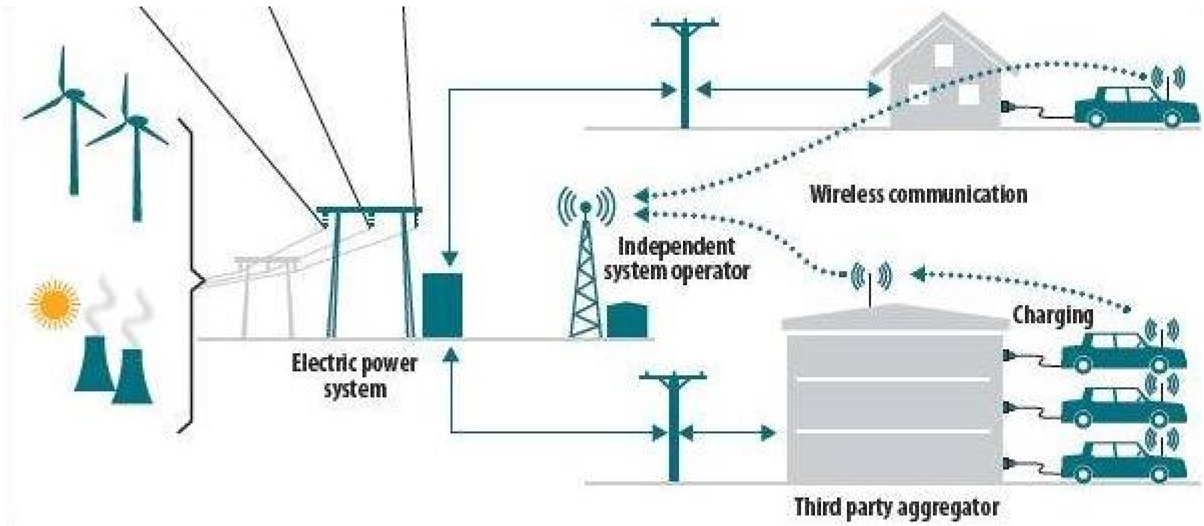


Figure 2-10 Components of a V2G system

Generally the average utilization of central power plants is 40-50%, while the utilization factor of electric vehicles is less than 10%. The light motor vehicles (less than 2 tons) are idle for a period of 20-22 hours a day [37]. If 2 million of these vehicles in Denmark [38] would supply 20 kW each,

they could provide 40 GW of electricity. This means the total average power requirement of 4 GW in Denmark could be supplied by the power capacity of only 10% of these vehicles.
There are a lot of electric car models available in the market with high energy density and efficiency. The newest Tesla Model S in its medium performance version has a 100 kWh battery with an energy efficiency of 6.7 km/kWh [39]. The average driving mileage in Denmark is 40 km, so from a simple calculation the net energy available in the battery after the daily driving is 93 kWh when the vehicle is fully charged.

In Chapter 5 (EV revenues from participation in V2G) it will be analysed the benefit of the EV owners when participating in V2G.

2.6 Conclusion

In this chapter the state of the art has been presented. This will be used as a theoretical background when simulating the aggregation of EV in dumb charging and smart charging, in chapters 4 and 5.
In the next chapter the EV driving data will be presented, in terms of driving patterns, arriving times, energy needs etc.

3 EV driving data

3.1 Introduction

Although batteries are still barriers in the EV's world, there is lot of research focused on the integration of EVs into power systems. In this section it is going to be explained some of the driving patterns and charging times studied from the Danish perspective. This will help to understand the results exposed in Chapter 4 and Chapter 5 about the simulations done.

3.2 The driving pattern

Despite the fact that every year there are more people owning an EV, there are still too few to get a real EV driving pattern. Nevertheless, it can be accepted that EV users will have the same driving pattern as those who use an ICE car [40].
Apart from that, the driving distance information, the available periods for charging, the initial State Of Charge (SOC) of the batteries and energy consumption will have to be analyzed from real EV data. Also, the destination of each trip will help to determine the availability of EVs for charging and discharging.

There are three different data sources of conventional vehicles available. These data come from [40]:

- AKTA data (GPS-based data that follows the vehicles);
- MDCars (Database of Odometer readings).
- TU data (Danish National Transport Survey);

The AKTA data are based on the data recorded by GPS of a total number of 360 vehicles. The problem of this data is that the number of cars is not enough to have a general conclusion of the driving pattern. Apart, the information was only collected from families with only one car who lived in a specific place. So the results might not be very accurate [40].

The second source, the MDCars, is a database that come from the reading of the mileage recorded by the odometer at the vehicle inspections. This data is nationwide and includes different types of vehicles. Eventhough, the data only includes the total number of an entire year for commercial vehicles and two years for private cars. Hence, this data can only be used to support the data on commercial vehicles [40].

TU data, which is provided by the Technical University of Denmark, is a Danish National Travel Survey. The data collected from this survey describe certain aspects of how Danish residents travel [41].

The figures below (Figure 3-1 and Figure 3-2) show both: the total transport length measured in km for each means of transport, and the numbers of trips each type does . It can be seen that for both graphs, although Denmark is promoting the use of public transport and of bicycles, vehicles are still one of the main transport within the country. Still many people use the car to go to work, or moving around cities. So it is supposed that EVs will have the same behavior as actual vehicles have.

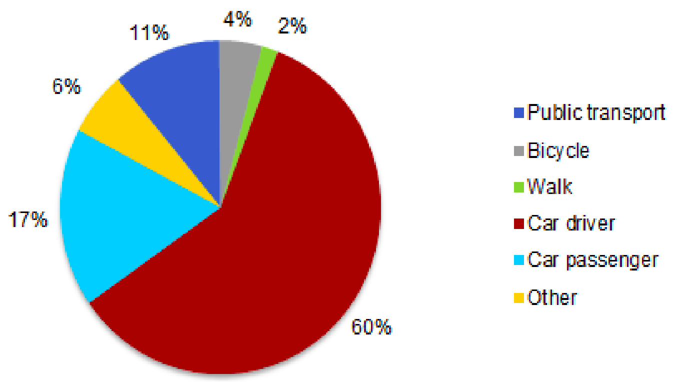


Figure 3-1. Distribution on transport means (km) 2014 [41].

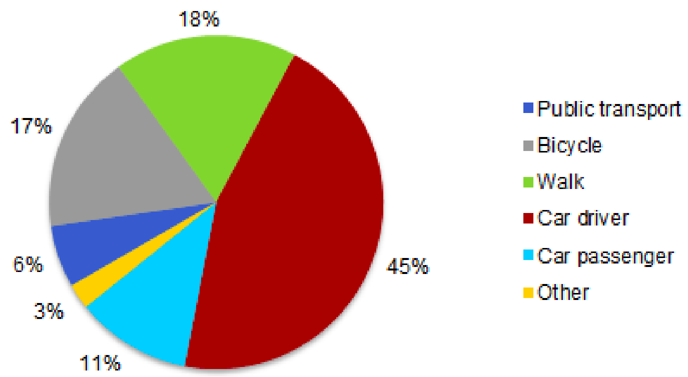


Figure 3-2 Distribution on transport means (trips) 2014 [41].

The average driving distance in Figure 3-3 shows that the highest distance travelled is 55 km, driven on Friday. The overall average distance is 47.86 km [42].

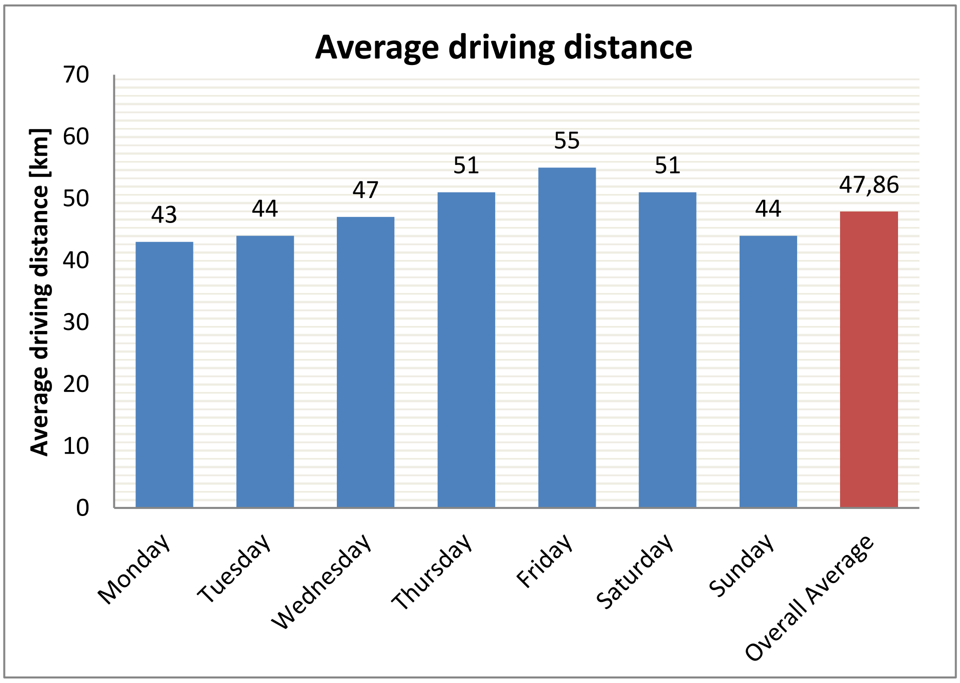


Figure 3-3. Average daily driving distance of passenger cars in Denmark [42]

In Figure 3-4 and Figure 3-5 it is shown how the trips are distributed in Denmark according to its purpose. In the first one, the graph is based on how many km people drive and in the second one how many trips depending on their plans.

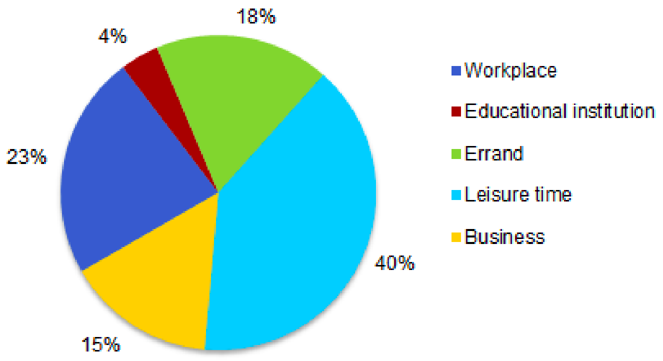


Figure 3-4. Distribution on trip purpose (km) 2014 [41].

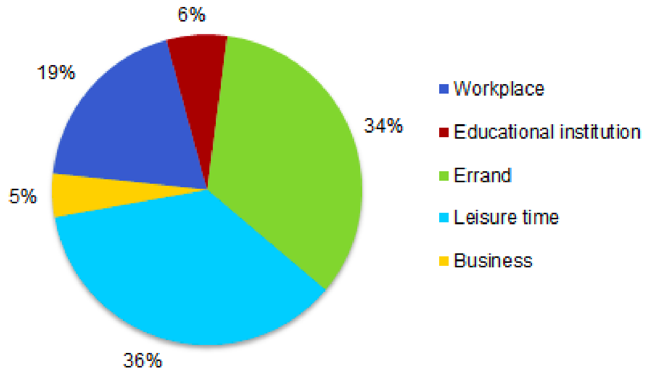


Figure 3-5. Distribution on trip purpose (trips) 2014 [41].

3.2.1 Charging profiles

During 2014 the Center of Electric Power and Energy (CEE), from the Technical University of Denmark, carried out a study based on the real driving behaviors in the Nordic Area. Regarding this study [43], the different charging profiles for EVs are normally calculated with different charging patterns. These include the dumb charging, the timed charging and, finally, the spot price based charging.

Dumb Charging refers to the uncontrolled charging of EVs, as explained in chapter 2 (Dumb charging). In this case two scenarios were studied: one referring to charging the vehicles whenever they are parked, and the second with just charging them when they are parked at home. As in this project it is analysed the aggregation of EVs when they are plugged in at home, it will be just shown the results of this case of study [43].

In Figure 3-6 and Figure 3-7 it can be seen the average load consumed among one day. The bright blue line regards Denmark's performance. During weekdays the peak takes place around 17h and 18h, while in weekends it can't be remarked any critical hour. From 10 in the morning until midnight, there is more a less the same load consumption.

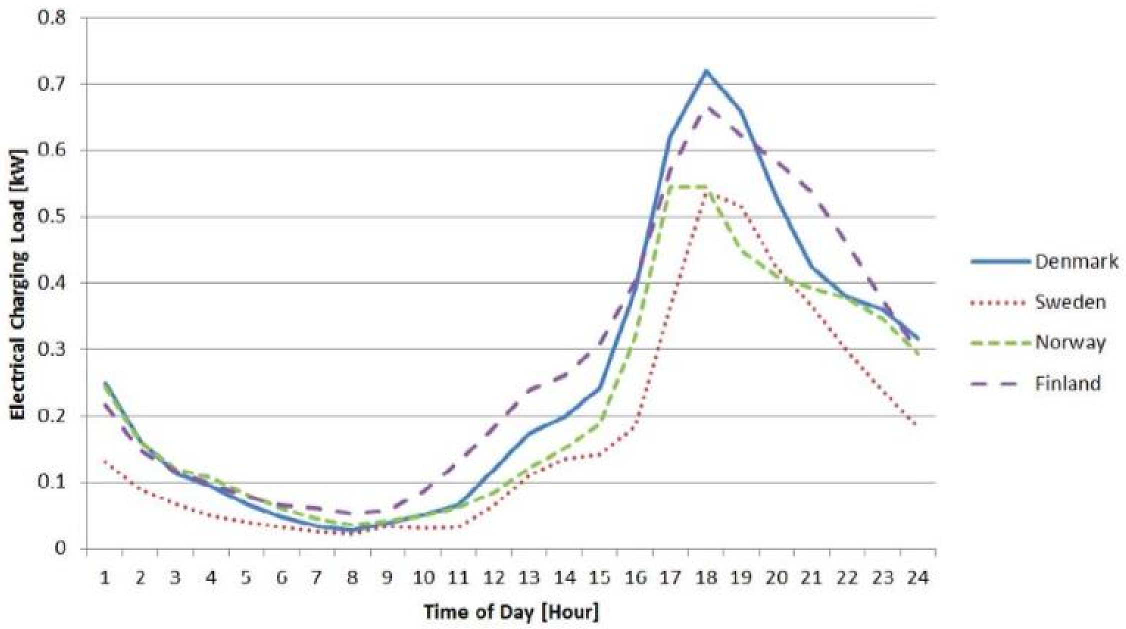


Figure 3-6. Average load with Dumb Charging at home on weekdays [43].

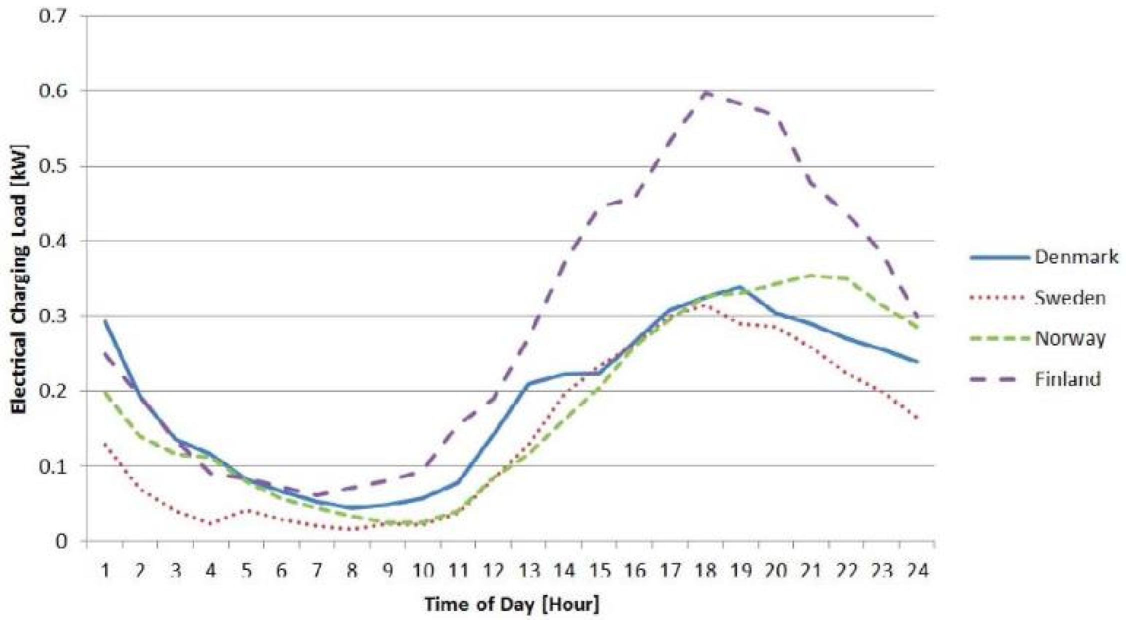


Figure 3-7 Average load with Dumb Charging at home on weekends [3].

Timed Charging is the term used when there is a schedule to charge the vehicle. So, EVs will be charged during a specific period of time, when the demand is low [43]. In the study from the Nordic area it was assumed that this time was between hour 21 and hour 23. As it can be seen in the next graphs, the results show that there is not a big difference between weekdays and weekends. This is obvious due to the fact that this type of charging is done in a certain period of time. Also it justifies the existence of a steep spike during last hours in the afternoon. As shown in Figure 3-8 and Figure 3-9, the charging is done from last hours of afternoon until midnight. So, in this case, the charging is controlled.

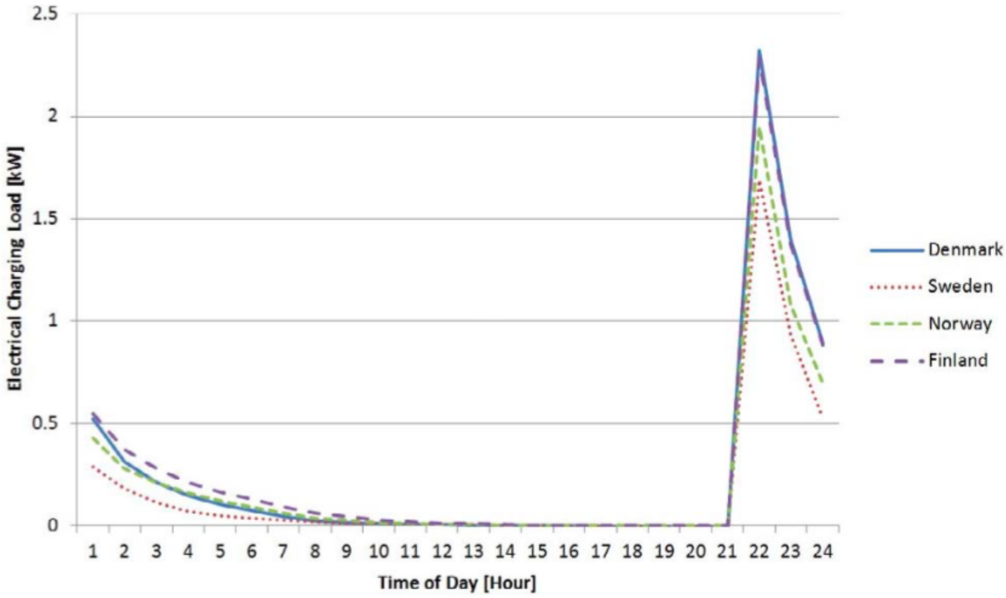


Figure 3-8. Average load with Timed Charging on weekdays [43].

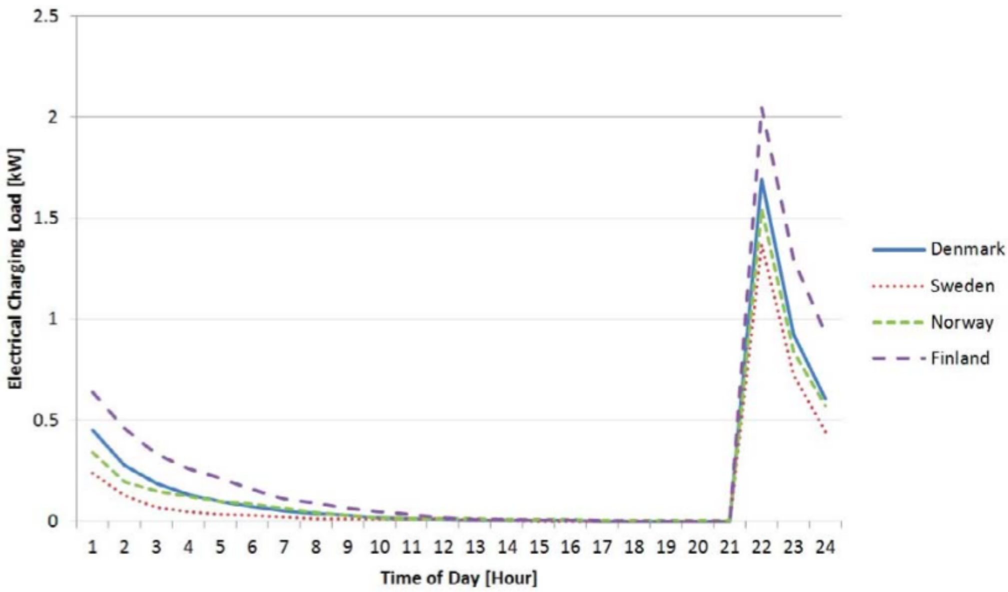


Figure 3-9 Average load with Timed Charging on weekends [3].

Spot Price Based Charging regards to an optimized charging. This means the charging period will be based on the expected electricity spot prices of the Nord pool electricity market. The aim is to minimize the charging cost with the energy requirement constraints of each individual vehicle respected [43]. As in last figures (Figure 3-10 and Figure 3-11), the average load peak takes place during a certain period of time. This is because it is normally at night when the electricity prices are the lowest.

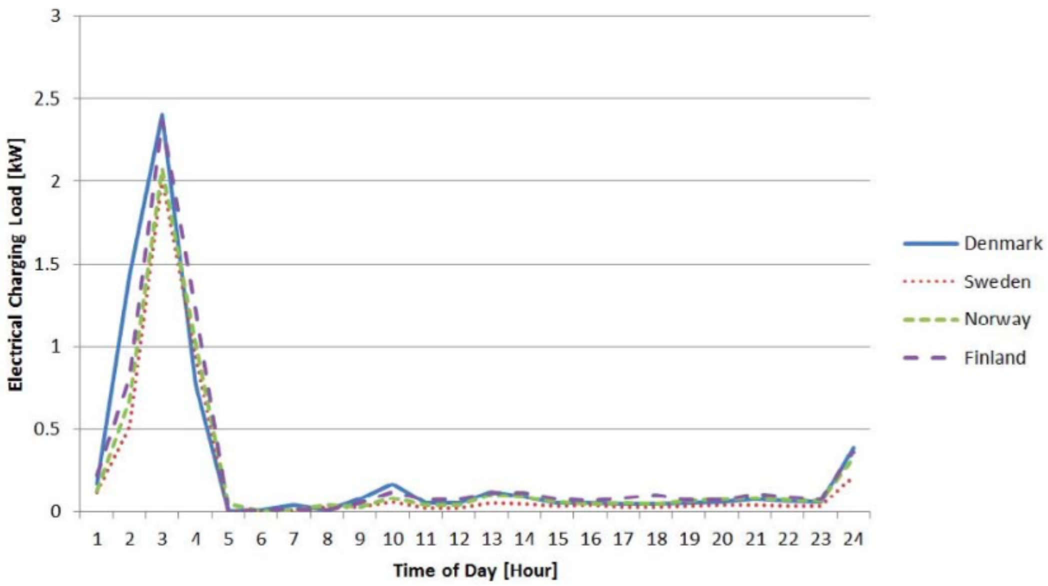


Figure 3-10. Average load with Spot Price Charging on weekdays [36].

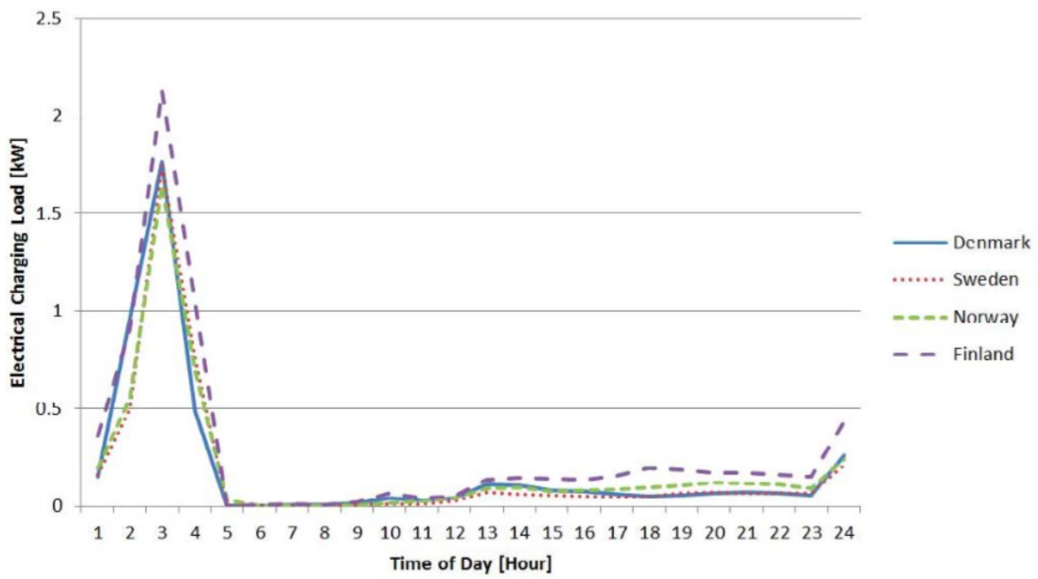


Figure 3-11. Average load with Spot Price Based Charging on weekends [3].

In this thesis, it has been assumed that the charging time will occur when the EVs are parked at home. So, as it is shown in Figure 3-12 these periods are before leaving home in the morning, and during evening after arriving home. Hence, this two times are indispensable for the simulation of the cases.

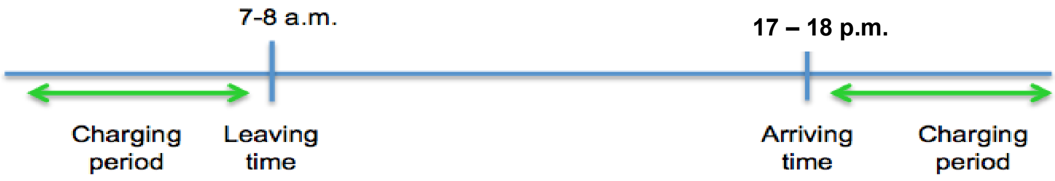


Figure 3-12 Representation of the charging time for EVs in one day.

Usually, the arriving and leaving time of EVs is similar in most countries, since people go to work during morning and go back home by evening. Regarding these, the data used in this project is based on A Statistical Analysis of EV Charging Behavior in the UK [44].

The number of plug-ins per day are presented in Table 3-1. It is important to remark that approximately the 70% of EVs are charged only once a day. This statement is valid for both weekdays and weekends.

Table 3-1. Probability distribution functions of the number of the connections per day (%) [44].

No. Connections	1	2	3	4	5	6	7+
Weekday	71.26	21.15	5.41	1.51	0.44	0.14	0.09
Weekend	68.99	21.51	6.62	1.9	0.63	0.24	0.11

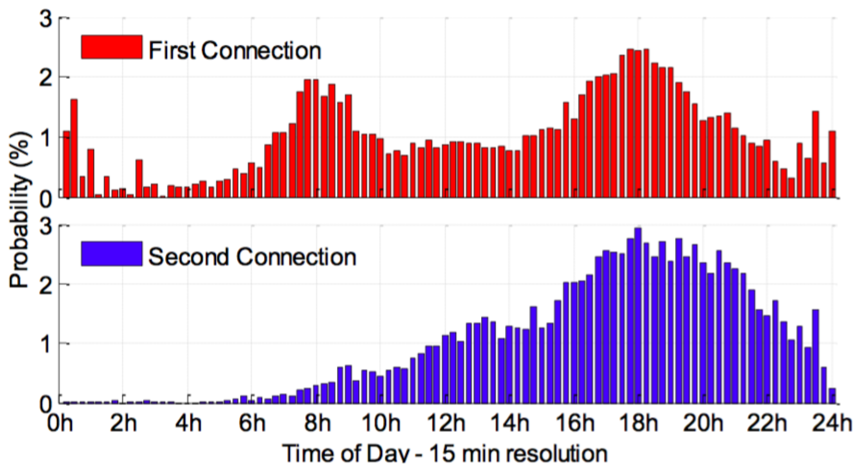


Figure 3-13 Probability distribution functions (PDF) of the start charging time per connection – Weekday [44].

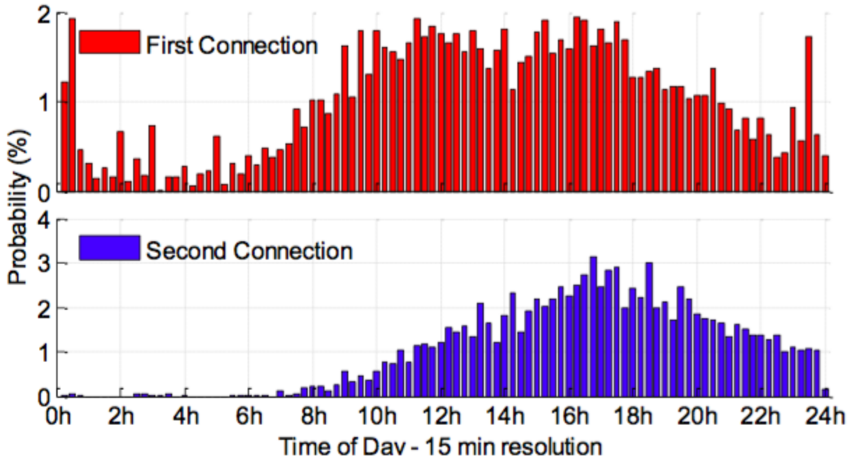


Figure 3-14 Probability distribution functions (PDF) of the start charging time per connection – Weekend [4].

As it can be seen in previous Figure 3-13 and Figure 3-14 , the hours of charging vary between weekday and weekend. However, during weekdays, the first connection is usually earlier than 8h (before going to work) or at 18h (after work). About the second connection, this normally takes place at 6 pm. During weekends the first connection can start between 9h and 18h and the second around 16h.

3.2.2 Energy consumption of EVs

As stated in [40] the average consumption of an electric vehicle for a home passenger ranges between 0,12 kWh/km and 0,18 kWh/km. Even though, there exist other sources such as [45] which indicates that this average can go up to 0,27 kWh/km. So, in this project, EVs have been assumed to consume 0,20 kWh/km. According to this, the energy needed can be calculated as:

$$E\ [kWh] = 0.20\ [kWh/km] \times \text{Distance travelled each day [km]} \qquad (2)$$

3.3 Generation of stochastic data

In order to do the simulations of dumb and smart charging in next chapters, it is necessary to have the data about arriving times and distances travelled during the day. To generate this data, different probability distributions have been used. For the arriving times, a normal distribution has been used, whereas in the case of the kilometers travelled it has been used a Weibull distribution. Both have been based on the driving patterns explained before (Charging profiles).
Considering that most vehicles arrive home at around 17h, for the arriving times, a normal curve has been established with a mean of 17. It can be seen in Figure 3-15 that most vehicles arrive home between 13 and 20h. The list of the arrival times from Figure 3-15 are exposed in the Appendix.

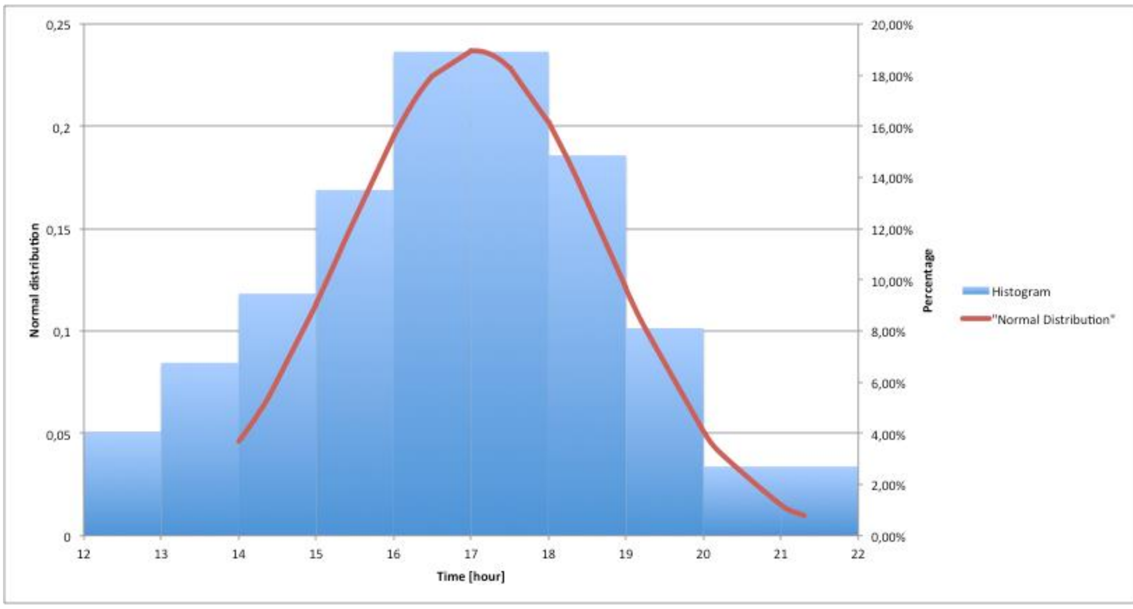


Figure 3-15 Normal distribution about EV arriving times

About the distances travelled, and considering the averages explained in The driving pattern (Figure 3-3), it has been obtained the following histogram (Figure 3-16). It can be seen that most vehicles drive for less than 50km and just few of them drive for more than 60km. Since this is random data (the script from Matlab can be seen in Appendix) it is normal that some vehicles exceed the average distance.

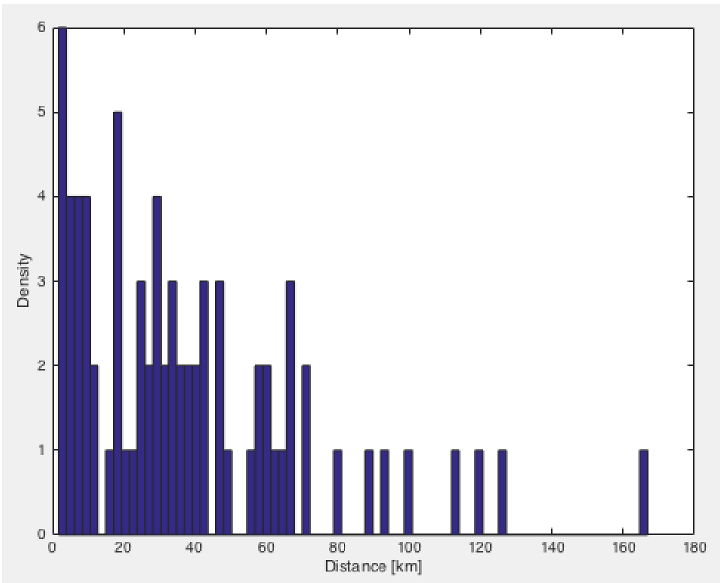


Figure 3-16 Histogram of the Weibull Distribution for distances travelled

Once distances are collected, it is possible to determine the charging time needed by each vehicle. This can be done using the following equation that will be used in both, Dumb charging of EVs and Simulation of smart charging in winter weekday.

$$Charging\ time\ [h] = 0{,}2\ \frac{kWh}{km} \cdot \frac{Distance\ travelled\ (km)}{Charging\ power\ (kW)} \tag{3}$$

3.4 Conclusion

This chapter has been mainly focused on the description of driving patterns. As it has been explained, it is important to analyse the driver's behaviour in order to understand the energy needs from the EVs, and consequently their charging time.

Also, these patterns help to create different charging plans that, at the same time, will help the grid not to be overloaded during certain hours. As long as people continue applying dumb charging to their EVs, it will remain the possibility of having some issues on the grid.

So, based on the explained profiles, in next chapters, it will be simulated the aggregation of EVs to see how the grid performs in each situation.

4 Dumb charging of EVs

In this chapter it is analysed the performance of the residential grid when dealing with dumb charging of EVs. The simulation is done by implementing 4 base case scenarios, during weekday and weekend in summer and winter. The grid is simulated initially without EVs, then with EVs plugged-in in three different levels of charging power, taking into account the grid constraints. Finally, the transformer loading and line losses of all scenarios are shown and an overall conclusion is made.

4.1 Introduction

The ambitious goal of Danish government for a large-scale integration of renewables, which has been explained in the previous chapters, won't be achieved without the implication of EVs. Since they are considered to be a kind of distributed energy resource (DER), EVs can cope with the fluctuations from wind power [43].

To analyse the impact of the EVs in the distribution grid, in terms of line and transformer loading and voltage limits, the base cases will be simulated with DigSilent Powerfactory using the grid in Figure 4-1.[46].

The grid is radial type with five feeders. Each one has a different structure and contains different number and type of loads. This could imply an uneven distribution of EVs in each feeder, due to different loading and distance from the main busbar. There are 75 houses in the grid, randomly distributed and divided in three consumption cathegories (L- low consumption, M – medium, H – high). This is based on the annual consumption data provided in [47]. The power factor is considered 0.97. It has been assumed that each house will have one EV and the maximum charging power is 11 kW.

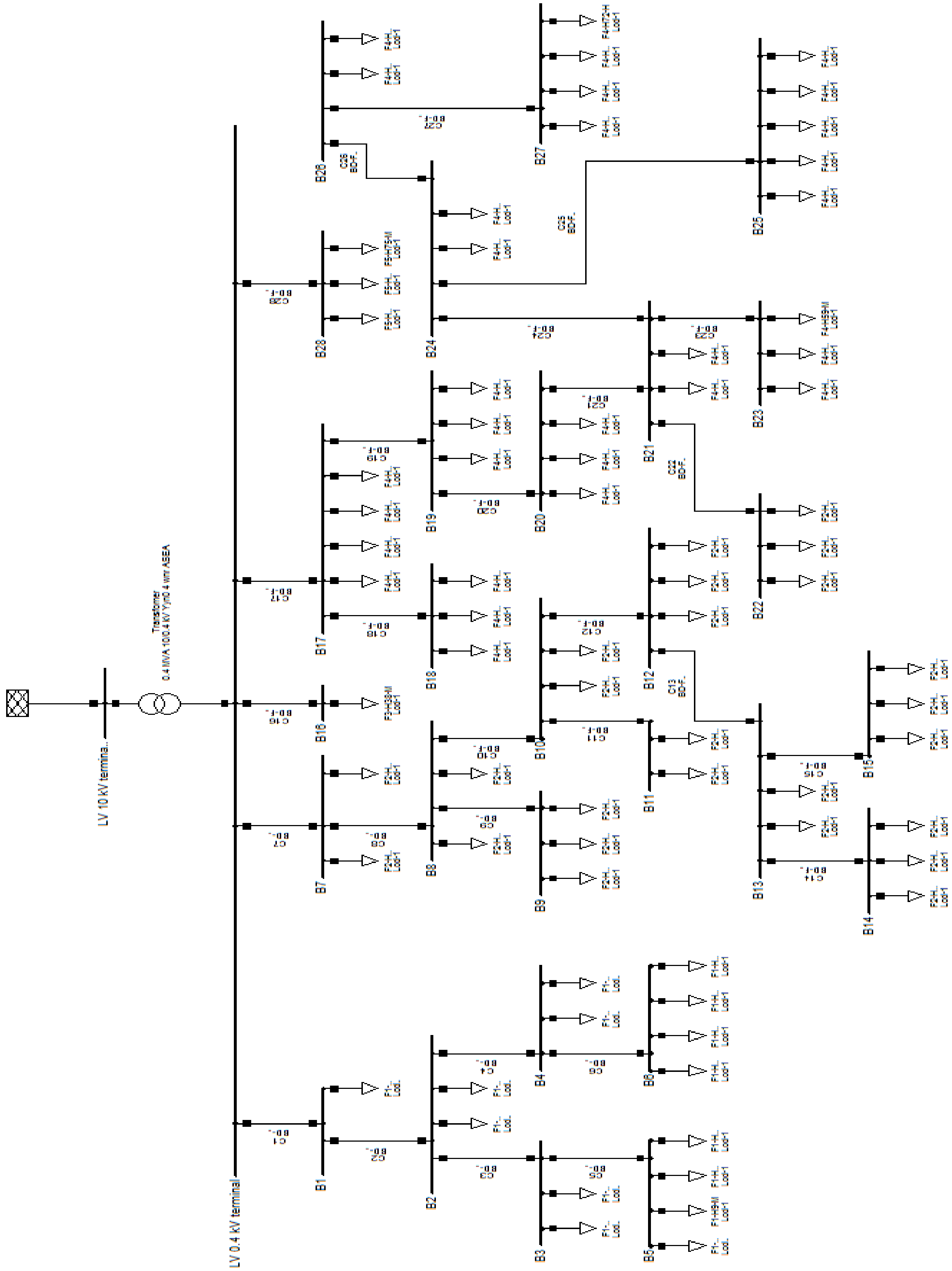


Figure 4-1 Distribution grid used in the simulation [46]

In Table 4-1 are shown the different loads contained in each feeder. An example of this is F1-H11-L which means **F**eeder **1** – **H**ousehold **11** - **L**ow Consumption (M means medium and H means high).

Table 4-1 List of loads from each feeder of the grid.

Feeder 1	Feeder 2		Feeder 3	Feeder 4		Feeder 5
F1-H11-L	F2-H28-L	F2-H36-M	F3-H38-M	F4-H39-M	F4-H56-L	F5-H73-H
F1-H6-L	F2-H32-L	F2-H22-H		F4-H40-M	F4-H57-M	F5-H74-M
F1-H1-M	F2-H37-L	F2-H23-H		F4-H41-M	F4-H58-M	F5-H75-M
F1-H13-M	F2-H56-L	F2-H24-H		F4-H42-M	F4-H59-M	
F1-H14-M	F2-H16-M	F2-H31-H		F4-H43-M	F4-H60-M	
F1-H15-M	F2-H17-M	F2-H34-H		F4-H44-M	F4-H61-M	
F1-H2-M	F2-H18-M			F4-H45-H	F4-H62-M	
F1-H3-M	F2-H19-M			F4-H46-M	F4-H63-M	
F1-H5-M	F2-H20-M			F4-H47-M	F4-H64-M	
F1-H7-M	F2-H21-M			F4-H48-L	F4-H65-M	
F1-H8-M	F2-H25-M			F4-H49-M	F4-H66-L	
F1-H9-M	F2-H26-M			F4-H50-M	F4-H67-M	
F1-H10-H	F2-H27-M			F4-H51-M	F4-H68-M	
F1-H12-H	F2-H29-M			F4-H52-M	F4-H69-M	
F1-H4-H	F2-H30-M			F4-H53-M	F4-H70-M	
	F2-H33-M			F4-H54-M	F4-H71-M	
	F2-H35-M			F4-H55-M	F4-H72-H	

In Table 4-2 and Table 4-3 some parameters of the grid are shown.

Table 4-2 Parameters of the transformer used in the grid.

Rated Voltage	10/0.4 kV
Rated Power	0.4 MVA
Nominal Frequency	50 Hz
Short circuit voltage uk of positive sequence impedance	4%
Copper losses of positive sequence impedance	4.3 kW

Table 4-3 Parameters of all lines from the grid.

Lines	L3, L4, L5, L6, L9, L11, L14, L15, L16, L18, L22, L23, L25, L26, L27, L28
Parameters	Rated voltage: 1kV. Rated current: 0.14 kA. Resistance R': 0.6417 ohm/km. Reactance X': 0.078539 ohm/km. Resistance R0': 2.5667 ohm/km. Reactance X0': 0.314159 ohm/km
Lines	L1, L2, L12, L13, L21, L24
Parameters	Rated voltage: 1kV. Rated current: 0.21 kA. Resistance R': 0.3208 ohm/km. Reactance X': 0.0753982 ohm/km. Resistance R0': 1.2833 ohm/km. Reactance X0': 0.3015929 ohm/km
Lines	L7, L8, L10, L17, L19, L20
Parameters	Rated voltage: 1kV. Rated current: 0.27 kA. Resistance R': 0.2075 ohm/km. Reactance X': 0.072256 ohm/km. Resistance R0': 0.83 ohm/km. Reactance X0': 0.289026 ohm/km

In the following subsections it is going to be explained how the grid has been analysed and which have been the results obtained from each scenario.

4.2 Analysis of the households consumption data

The household consumption data used in this project is the average European domestic electrical consumption of some buildings in a neighbourhood. The houses are divided into low, medium and high electric energy consumption [47]. According to the data, the household's loads are different depending on the month. Also, they vary between weekday and weekend. Therefore 2 periods of the year are considered, summer and winter, and it has been taken January and July as reference months. More information about this data is provided in Appendix 1.

In Figure 4-2 is shown the daily consumption among weekdays and weekends, in the 2 selected periods of the year.

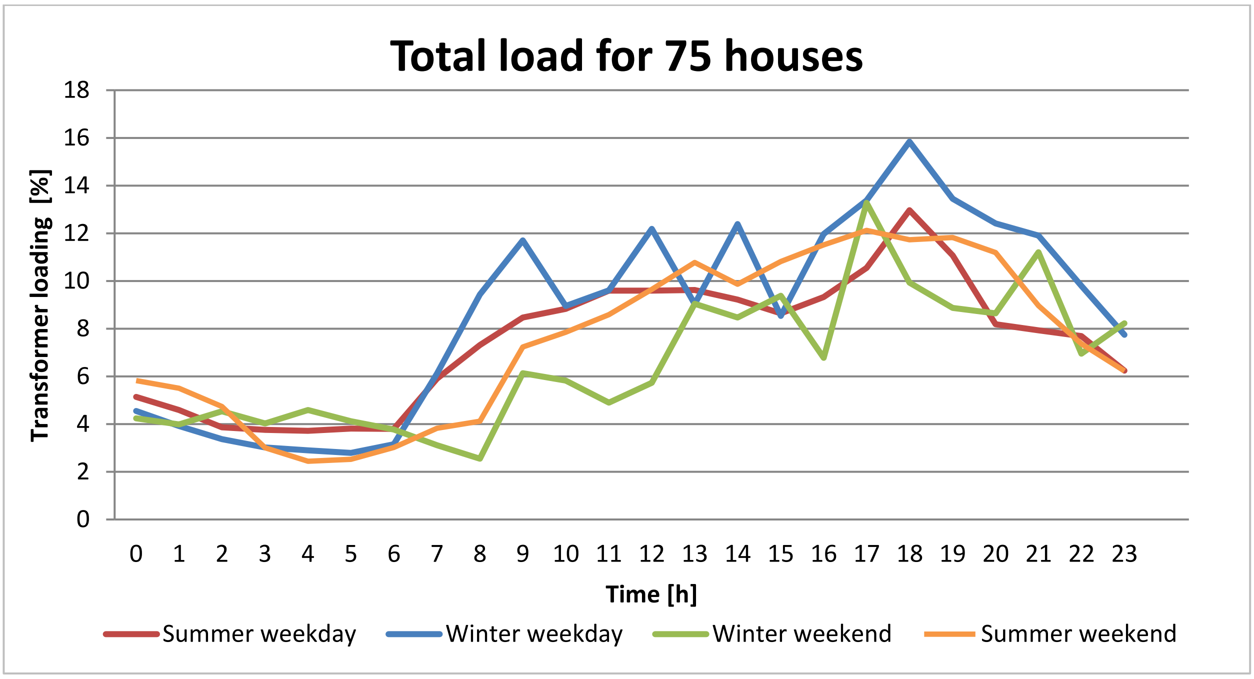


Figure 4-2 Daily consumption in January and July.

In a winter weekday there is a significant difference between the peak hours during weekdays and weekends. There is a higher consumption during winter, because of heating and lighting loads. In the weekdays, the maximum consumption is around 17:00 and 19:00, which corresponds to the time when people come back from work. While in weekends this peak takes place between 16:00 and 18:00.

4.3 Base case analysis

In this section the selected base cases are analysed: winter weekday, winter weekend, summer weekday and summer weekend. There will be four scenarios for each base case. Initially the normal grid operation without EVs will be analysed, then with the EVs plugged in with dumb charging mode with 3 different charging power levels. So, in order to see how this affects the grid, it has been simulated the aggregation of EVs when people come back from work. In winter weekday, there will be a scenario where consumers plug in their EVs as soon as they arrive home, according to the driving patters. In the rest of the scenarios it is assumed that consumers plug-in the EVs after 17.00, which coincides with the peak consumption hour, in order to see how the grid can handle the EVs in the worst case.

The average consumption of EVs is shown in Chapter 3 (Energy consumption of EVs).

The constraints of the grid simulation are 0.94<V<1.06 [p.u], Line and transformer loading <100% [48]. From (Charger power levels) in chapter 2, three levels of charging power have been tested: 3.7 kW, 7.2 kW, 11 kW. DigSilent Load Flow and Timesweep tools are used to analyse the grid.

4.3.1 Winter weekday

4.3.1.1 Without EVs

From Figure 4-2, the peak of the load demand is 15.84%, during 17.00 – 19.00. In Figure 4-3 the voltage magnitude of all the buses is shown, where it can be observed that the voltage drops at the end of each feeder. The total load is 60.66 kW. The most affected is Feeder 4, with busbars from 21-27 showing the highest drops, and the lowest value at busbar 27, 0.959 p.u. This is because this feeder is the most loaded and busbar 27 is the farther from the main busbar. However without EVs the grid limits are still fulfilled, but Feeder 4 may not be able to support many EVs.

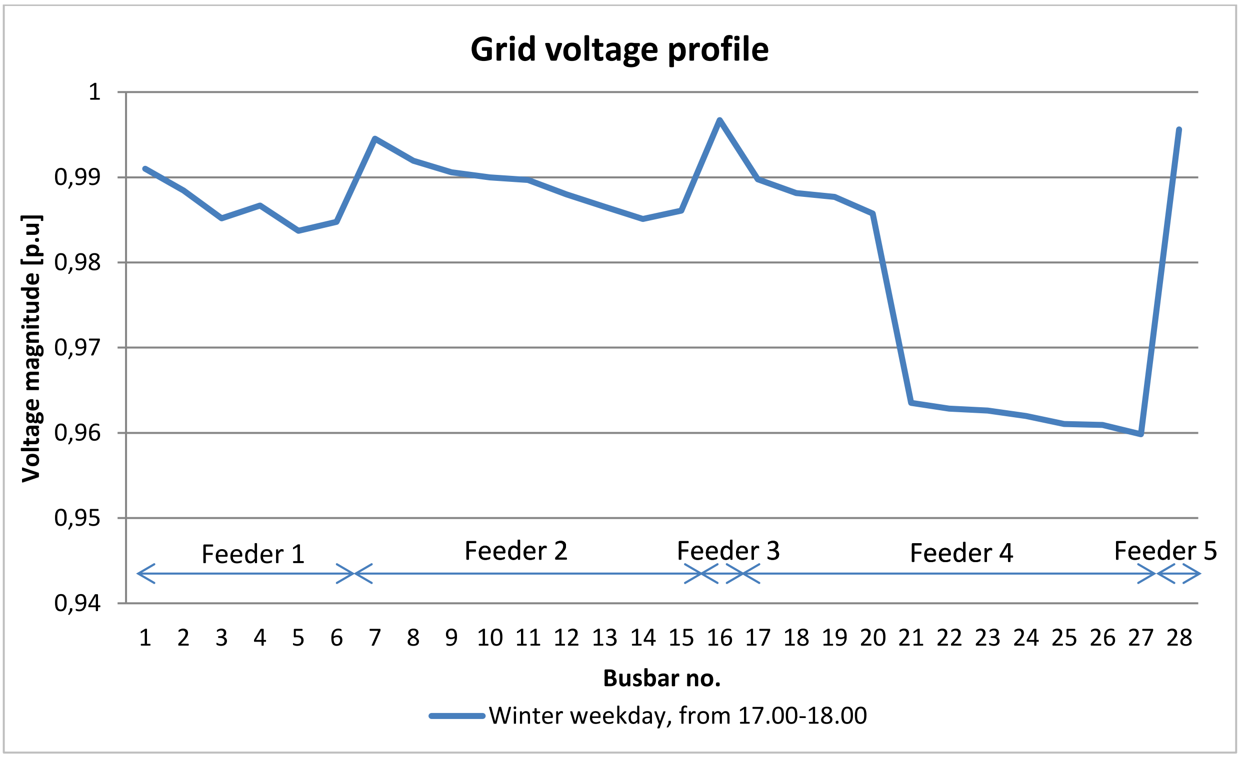


Figure 4-3 Busbars voltage in the peak hour without EVs. Winter weekday.

In Figure 4-4 the voltage drop of Busbar 27 is shown, during a whole winter weekday. The highest drop is around 18.00-19.00, which also corresponds to the load demand curve.

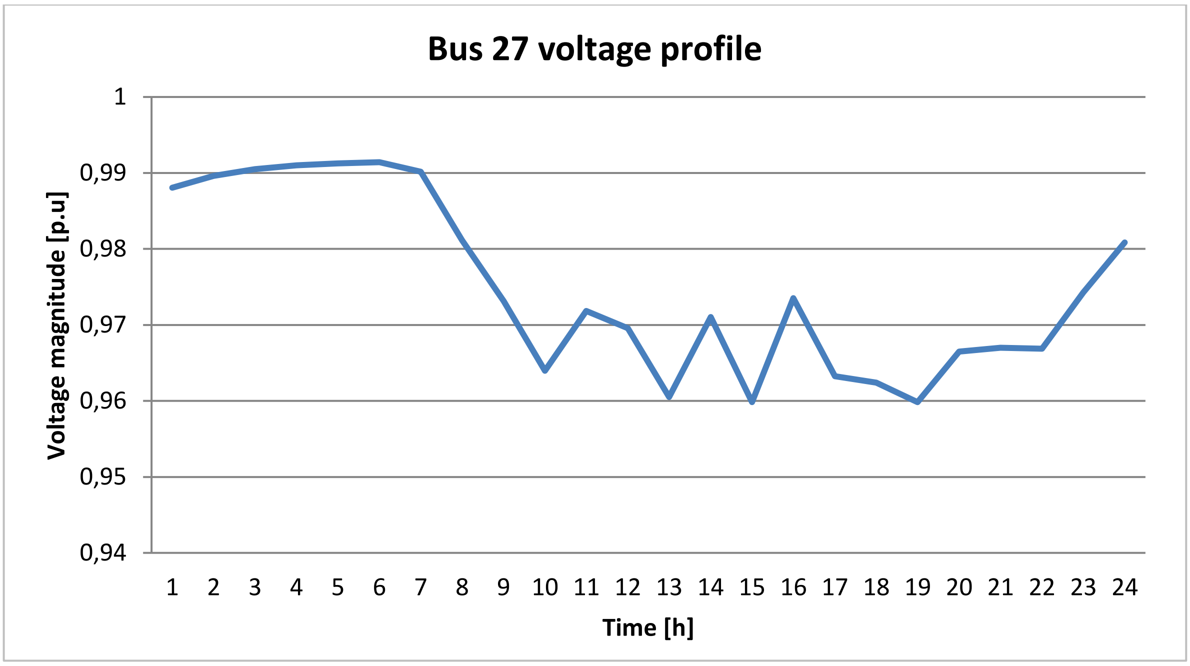


Figure 4-4 Busbar 27 voltage profile in a winter weekday without EVs.

4.3.1.2 With EVs

- 11 kW charging based on arriving times

Consumers plug-in their EVs as soon as they arrive home, according to the arriving times in (Generation of stochastic data). EVs will be charged at 11 kW in this scenario, and the grid capacity to provide electricity to all EVs will be tested.

The maximum number of EVs that the grid can support, without exceeding its limits is 61 (81.3% of the total EVs) and the transformer peak load is 209.1 kW (52.5%) (Figure 4-5). In Table 4-5 it can be seen that Feeder 4 can support only 20 EVs, (58.8 % of the feeder capacity). This because it is the feeder with the highest number of loads.

Table 4-4 11 kW charging of the EVs based on the arrival times. Winter weekday

	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Total
Bus no. connected with EVs	B1, B2, B3, B4, B5, B6	B7, B8, B9, B10, B11, B12, B13, B14, B15	B16	B17, B18, B19, B20, B21, B22, B23	B28	
No. of connected EVs	15	22	1	20	3	61
No. of houses	15	22	1	34	3	75
Percentage of connected EVs	100%	100%	100%	58,82%	100	81,33%

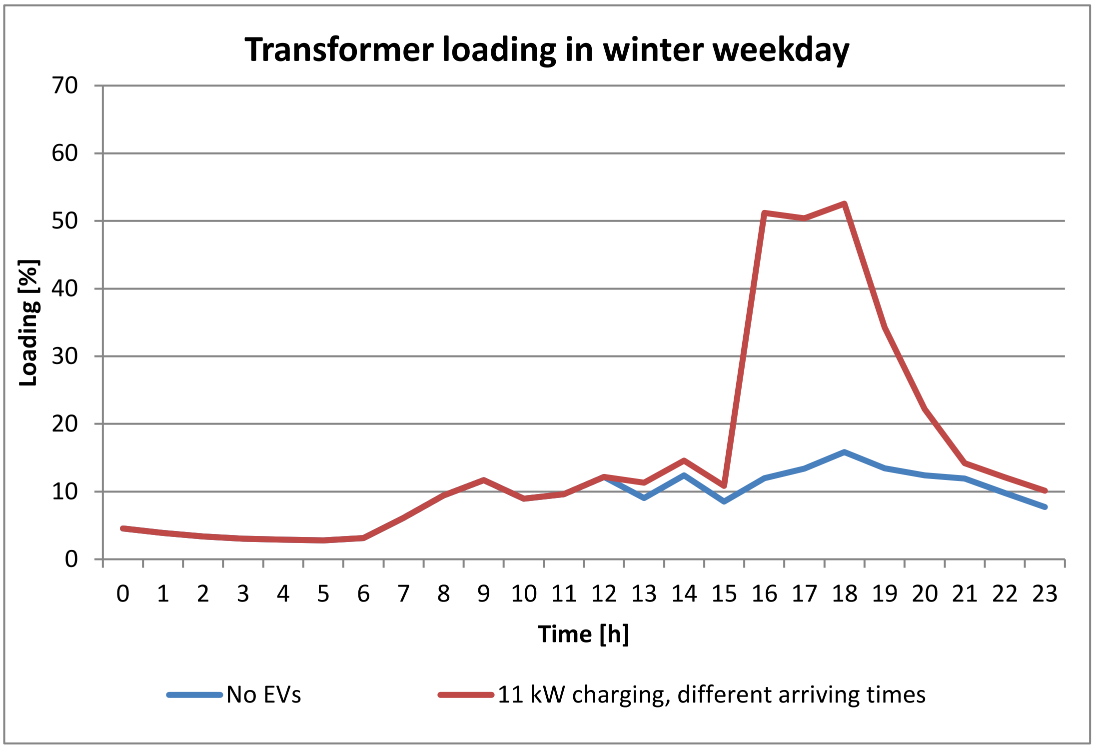


Figure 4-5 Transformer loading: 11 kW dumb charging vs No EVs. Winter weekday

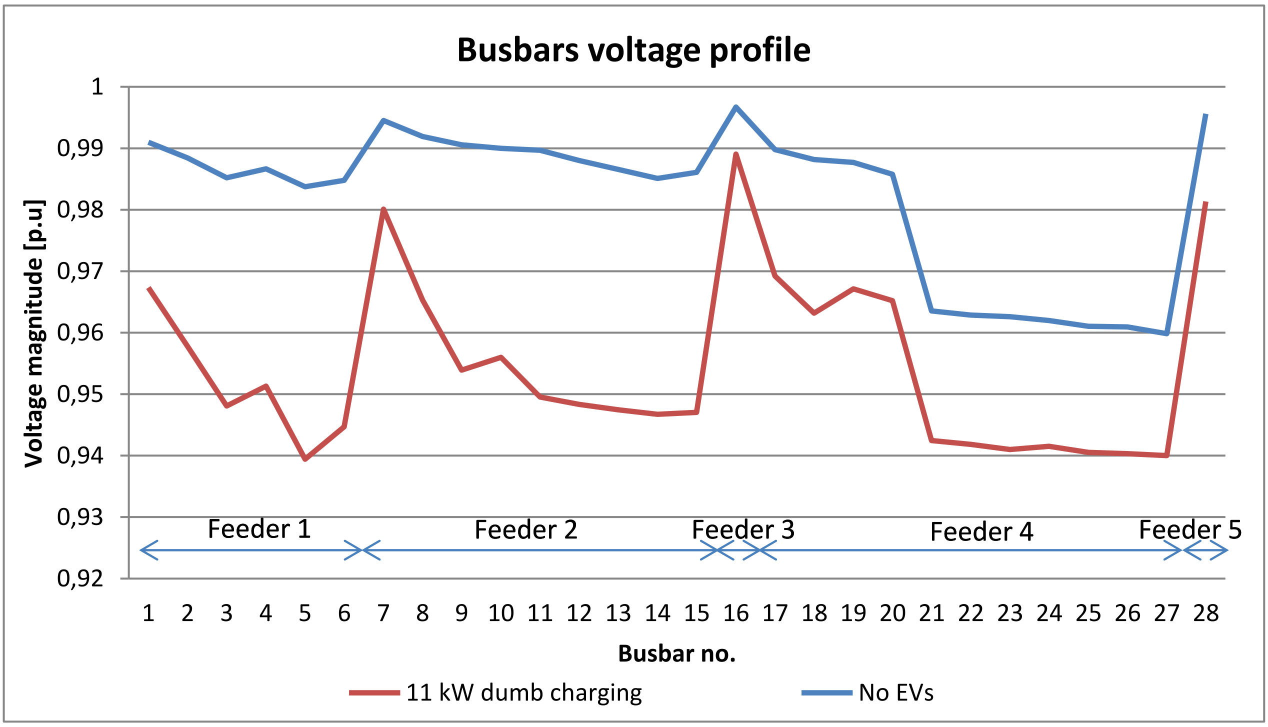


Figure 4-6 Comparison of busbars voltage in the peak hour without EVs and with 11 kW charging. Winter weekday.

In Figure 4-6 it is shown how the voltage drastically drops when EVs plug-in, being just above the limit in the feeder's extremes.

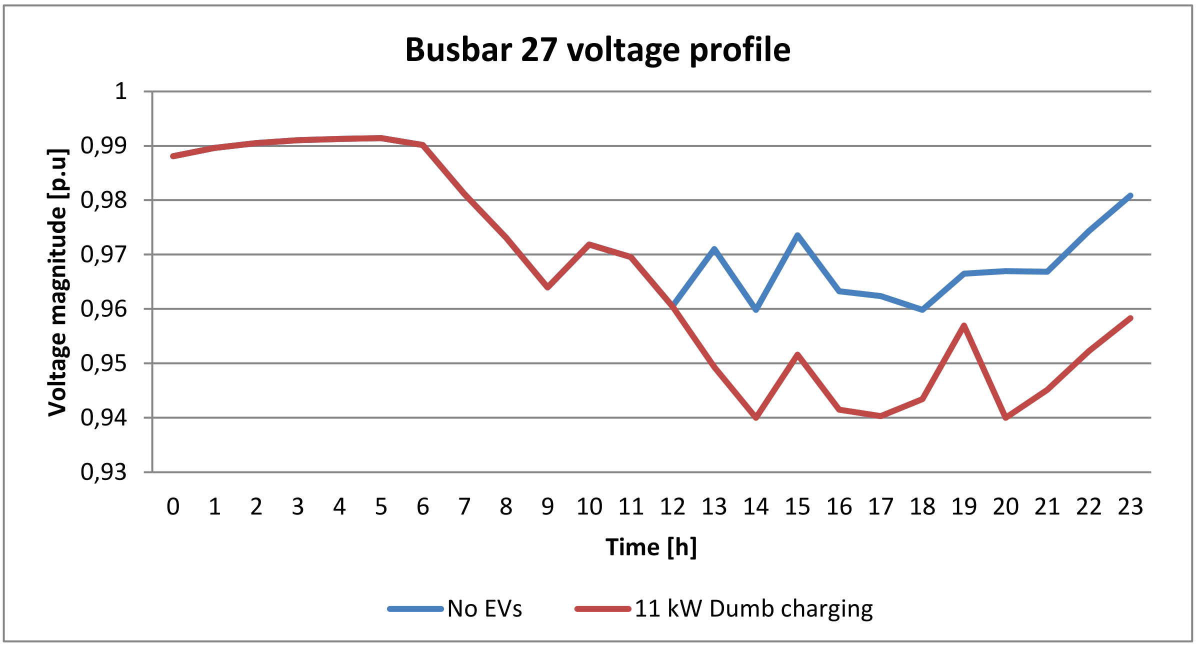


Figure 4-7 Busbar 27 voltage profile: No EVs vs 11 kW dumb charging, as consumers arrive home.

In Figure 4-7 the voltage profile of Busbar 27 is shown, being within the accepted range. Still it can't charge any EV. This proves that the consumers who are farther from the main busbar might have problems to charge their EVs in dumb charging mode.

In the following scenarios the EVs will be plugged in dumb charging starting from 17.00 and the charging time will depend on the charging power implemented. This is to see how many EVs the grid can support in the worst case.

- 11 kW charging

In this scenario EVs will be put into charging from 17.00-18.00. It is expected that charging the EVs at 11 kW may exceed the transformer rating and the voltage limits.

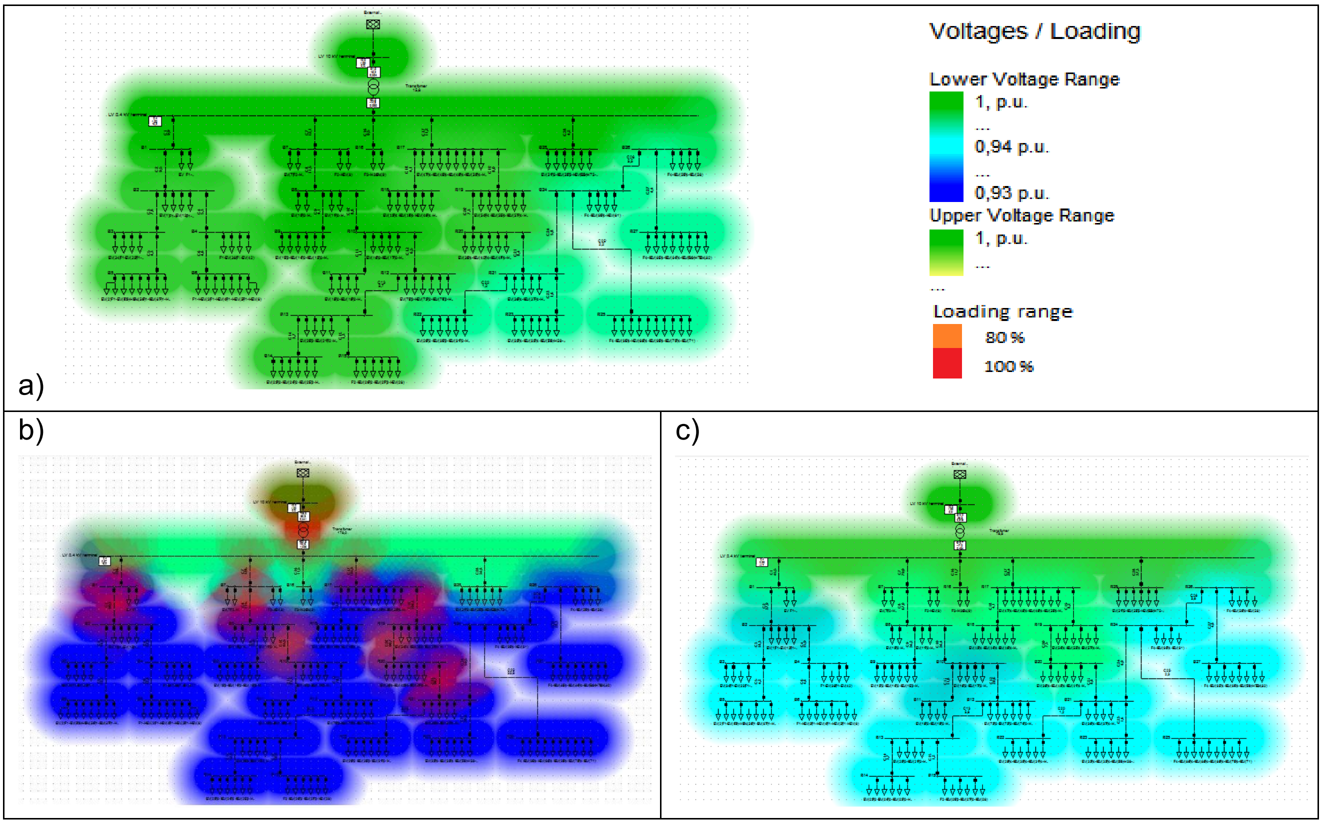


Figure 4-8 Loading & voltage magnitude mapping of the grid: a) no EVs b) all EVs (75) with 11 kW charging c) maximum EVs (24) with 11 kW charging.

In Figure 4-8 it is shown the mapping of the line&transfomer loading and voltage magnitude in the grid. In b) it can be observed that when all 75 EVs plug-in at 17.00, which is also the peak hour, the grid limits are violated. The transformer and many lines are overloaded and almost all busbars' voltage is below 0.94 p.u. In c) it is shown the mapping with the maximum number of EVs plugged-in, without exceeding grid limits.

The maximum number of EVs that the grid can support, without exceeding these limits is 24 (32 % of the total EVs) and the transformer load is 301.4 kW (78.83 %). In Table 4-5 it can be seen that Feeder 4 is the weakest of all, supporting only 3 EVs (8.8 % of the feeder capacity) in this case.

Table 4-5 11 kW charging of EVs. winter weekday.

	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Total
Bus no. connected with EVs	B1, B2, B3, B4	B7, B8, B9, B10, B11, B12	B16	B17	B28	
No. of connected EVs	5	12	1	3	3	24
No. of houses	15	22	1	34	3	75
Percentage of connected EVs	33.33 %	54.54 %	100 %	8.82 %	100 %	32 %

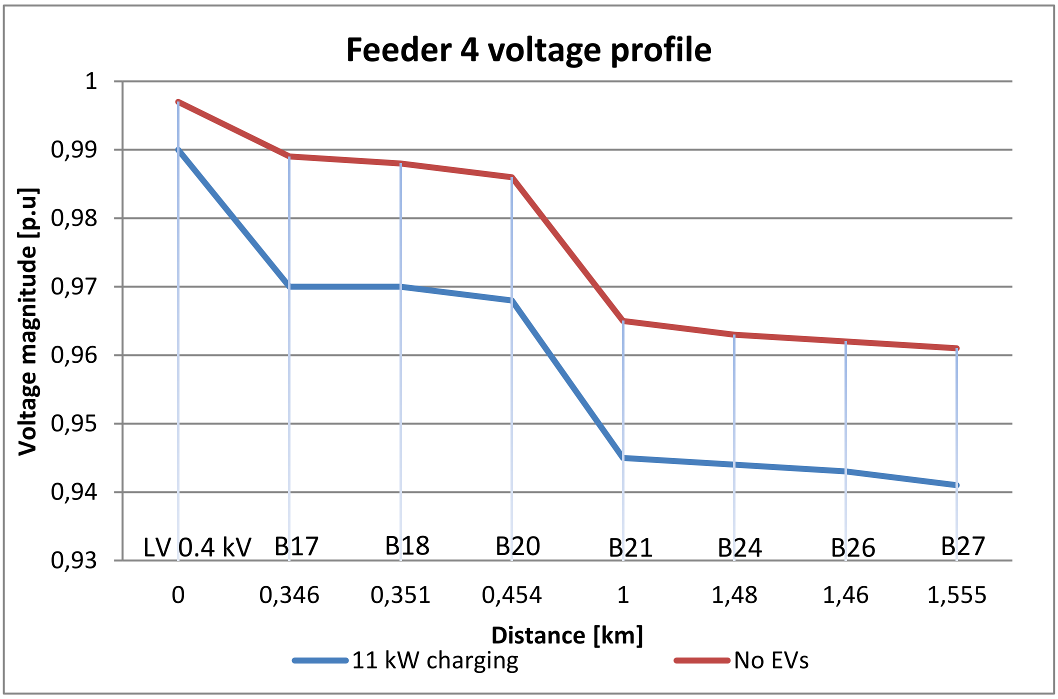


Figure 4-9 Comparison of Feeder 4 voltage profile in the peak hour without EVs and with 11 kW charging EVs (17.00-18.00) . Winter weekday.

In Figure 4-9 it is shown the voltage profile along Feeder 4. There are only 3 EVs charging at 11 kW and since in dumb charging mode, people plug-in the EVs as soon as they arrive home, which also corresponds to the peak demand. This is reflected in the voltage drop along the feeder, where the most distant busbars are the most affected, with no. 27 being just above 0.94 p.u.

- 7.2 kW charging

In accordance to the driving patterns in chapter 3 (The driving pattern), the average energy needed for the EVs is 8 kWh, and the available time for charging is from 17 to 8 of next morning. There is plenty of time to fully charge them and so less charging power could be implemented, in this case 7.2 kW will be analysed. Also more EVs can be integrated on the grid.
Since charging power is reduced, more time is needed to fufllfill the charging demands, so EVs will be charging from 17-18:30. The transformer load is 264.61 kW (69.16 %), in Table 4-6 it can be seen that Feeder 4 still can't support more than 15% of the EVs, with a total number of 31 in the grid (41.3 %). In this case the transformer loading is almost 10% less then with 11 kW charging, but 10% more EVs can be plugged in the grid.

Table 4-6 7.2 kW charging of EVs. winter weekday.

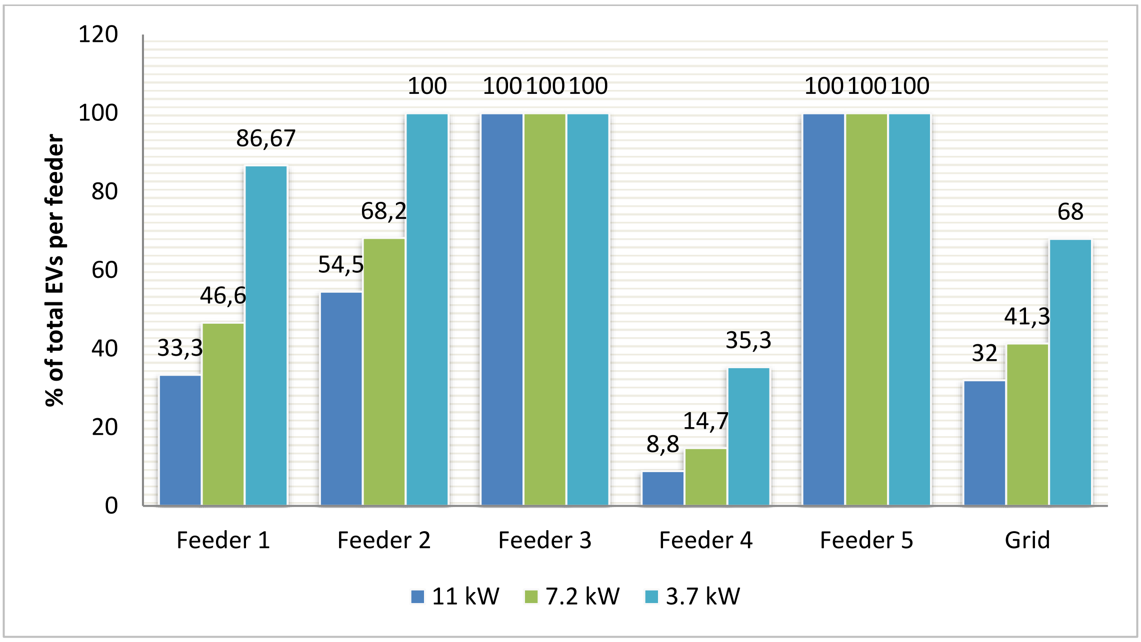
	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Total
Number of connected EVs	7	15	1	5	3	31
Number of houses	15	22	1	34	3	75
Percentage of connected EVs	46.67 %	68.18 %	100 %	14.71 %	100 %	41.33 %

- 3.7 kW charging

By reducing the charging power to 3.7 kW, the number of EVs in the grid should be almost doubled in comparison with the 7.2 kW case. EVs will charge from 17-19.30. The transformer loading is 231.8 kW (57.38 %) and Feeder 4 can support 12 EVs now (Table 4-7). The total number in the grid is 51 (68% of all), 26% more than the previous case with 12% less loading on the transformer.

Table 4-7 3.7 kW charging of EVs. winter weekday.

	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Total
Number of connected EVs	13	22	1	12	3	51
Number of houses	15	22	1	34	3	75
Percentage of connected EVs	86.67%	100%	100%	35.29%	100%	68%



Graph 4-1. Overall comparison of EVs integration in winter weekday.

As it can be seen in Graph 4-1 only by reducing the charging power more EVs can be integrated on the grid, without reforming the network and also fulfilling the charge demands of the EVs. In a winter weekday, the maximum number of EVs that can plugged-in with dumb charging is 51 (68% of all), with 3.7 kW charging power. The weakest is Feeder 4, supporting only 12 EVs (35.3% of feeder capacity).

4.3.2 Winter weekend

4.3.2.1 Without EVs

The total load is 51.93 kW with 13.2% peak of the transformer loading during 18-19. This is less than winter weekday since the peak demand during weekends is lower. As in the previous case, Feeder 4 is still the most loaded.

4.3.2.2 With EVs

- 11 kW charging

In this case the grid can support 26 EVs, slightly more than the weekday (34.6% of the total). An additional vehicle can be plugged in Feeder 4 but it still supports only 11.7 % of its capacity.

Table 4-8 11 kW charging of EVs. Winter weekend.

	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Total
Bus number with EVs plugged in	B1, B2, B3, B4	B7, B8, B9, B10, B11, B12	B16	B17, B18	B28	
Number of connected EVs	5	13	1	4	3	26
Number of houses	15	22	1	34	3	75
Percentage of connected EVs	33.3 %	59.09%	100%	11.7%	100%	34.6%

- 7.2 kW charging

Table 4-9 7.2 kW charging of EVs. Winter weekend.

	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Total
Bus number with EV's plugged in	B1, B2, B3, B4	B7, B8, B9, B10, B11, B12, B13	B16	B17, B18	B28	
Number of connected EV's	7	16	1	7	3	34
Number of houses	15	22	1	34	3	75
Percentage of connected EV'S	46.6%	72.7%	100%	20.5%	100%	45.3%

- 3.7 kW charging

Table 4-10 3.7 kW charging of EVs. Winter weekend.

	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Total
Bus number with EV's plugged in	B1, B2, B3, B4, B5, B6	B7, B8, B9, B10, B11, B12, B13, B14, B15	B16	B17, B18, B19, B20	B28	
Number of connected EV's	15	22	1	13	3	54
Number of houses	15	22	1	34	3	75
Percentage of connected EV'S	100%	100%	100%	38.2%	100%	72%

Graph 4-2 Overall comparison of EVs integration in winter weekend.

Graph 4-2 is shows the percentage of EVs that can be integrated in this case, which is slightly higher than the weekday due to the lower consumption. Still, Feeder 4 is not able to support many EVs.

4.3.3 Summer weekday

4.3.3.1 Without EVs

The peak loading of the transformer is 48.28 kW (13 %) from 18 to 19. Without EVs, even in the highest load consumption situation, the voltage drop is in an acceptable range for the grid. From Figure 4-10 the lowest voltage is at the end of Feeder 4, Bus 27 more precisely.

Bus 27 at the end of Feeder 4 is chosen in order to analyze the voltage drop for 24 hours. The highest drop is around 18.00-19.00, which also corresponds to the load demand curve.

4.3.3.2 With EVs

- 11 kW charging

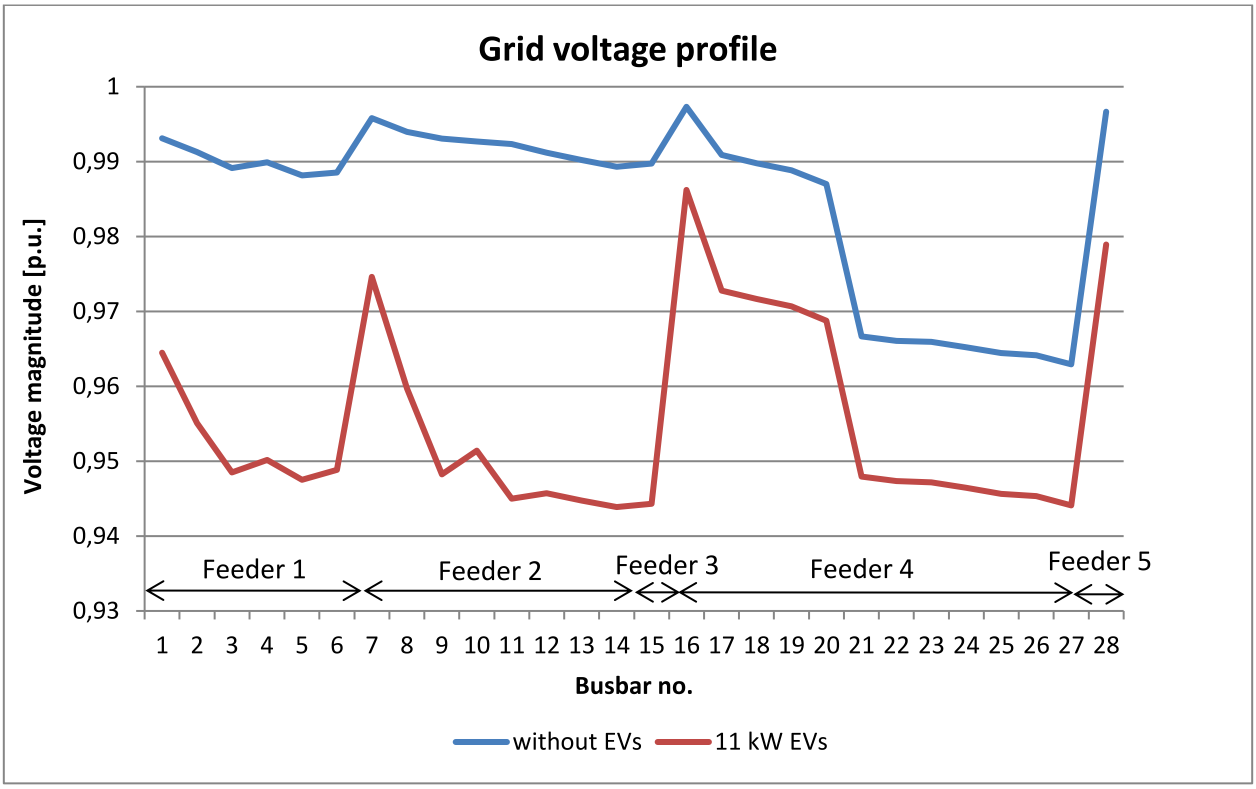


Figure 4-10 Busbar voltages comparison without EVs and 11 kW charging. Summer weekday.

In Figure 4-10 it can be seen how the busbars' voltage in drops drastically when EVs are plugged-in. Busbar 27 is now just above the allowed voltage limit (Figure 4-11).

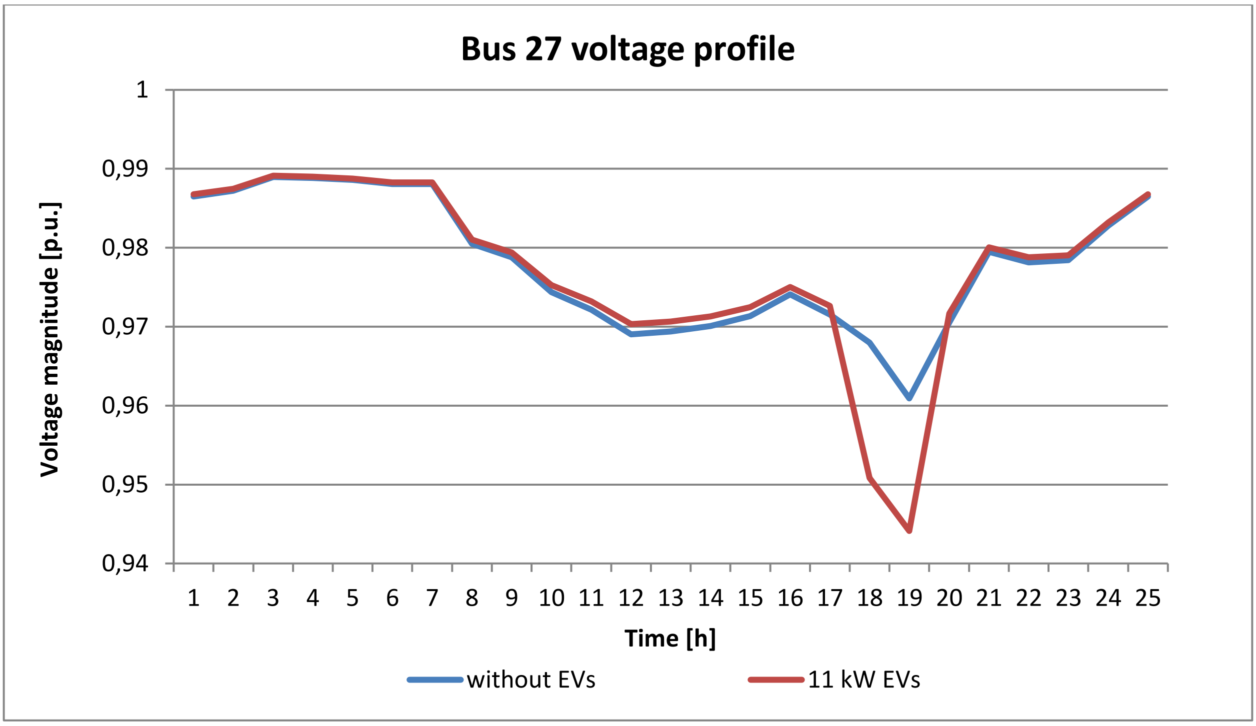


Figure 4-11 Busbar 27 voltages comparison without EVs and 11 kW charging. Summer weekday.

In this case, the grid can support 25 EVs connected (33.33 % of the total EVs), only 3 EVs in the Feeder 4, being the weakest feeder of all five feeders (8.82 % of the total EVs in Feeder 4) as shown in Table 4-11.

Table 4-11 11 kW charging of EVs. Summer weekday.

	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Total
Bus no. connected with EVs	B1, B2, B3, B4	B7, B8, B9, B10, B11, B12	B16	B17	B28	
No. of connected EVs	5	13	1	3	3	25
No. of houses	15	22	1	34	3	75
Percentage of connected EVs	33.33 %	59.09 %	100 %	8.82 %	100 %	33.33 %

- 7.2 kW charging

In this case there are 34 EVs connected to the grid, with Feeder 4 being again the weakest, with just 6 EVs connected. It can also be seen that lowering the charging power from 11 kW to 7.2 kW is a good plan to permit more EVs charging at the same time.

Table 4-12 7.2 kW charging of EVs. Summer weekday.

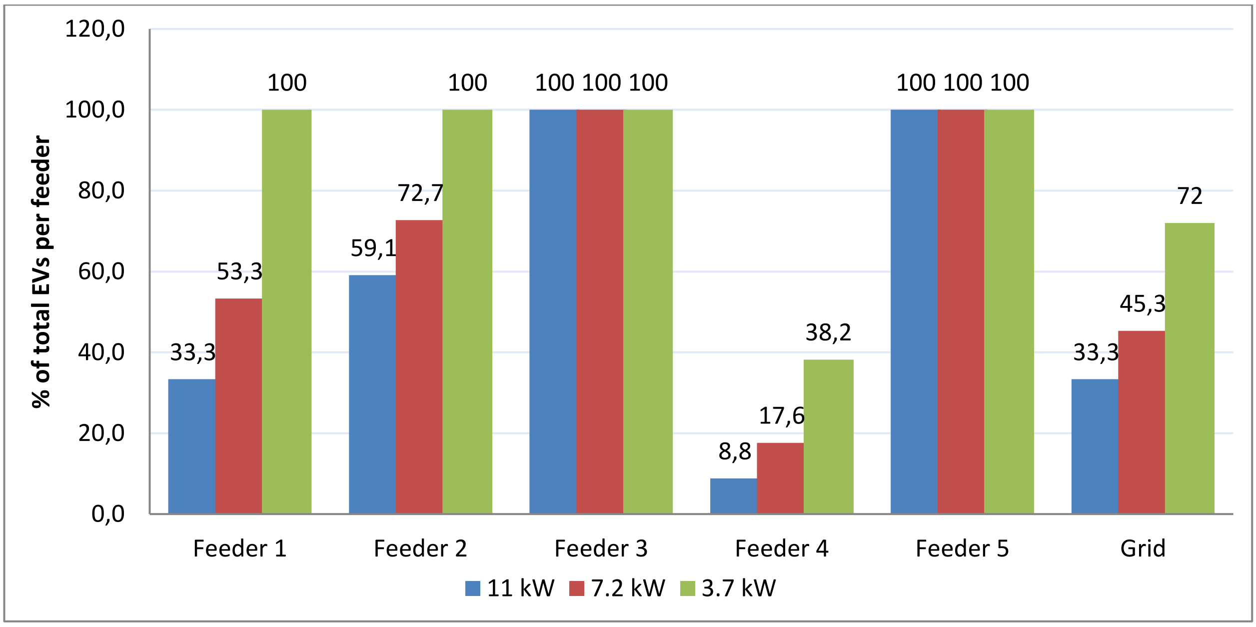
	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Total
No. of connected EVs	8	16	1	6	3	34
No. of houses	15	22	1	34	3	75
Percentage of connected EVs	53.33	72.73	100	17.65	100	45.33

- 3.7 kW charging

In this case, all feeders can support the maximum number of cars, except feeder 4, which can support only 13 EVs. The total number of EVs in the grid is 54 (72 %).

Table 4-13 7.2 kW charging of EVs. Summer weekday.

	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Total
No. of connected Evs	15	22	1	13	3	54
No. of houses	15	22	1	34	3	75
Percentage of connected EVs	100	100	100	38.24	100	72



Graph 4-3 Overall comparison of EVs integration in summer weekday.

In Graph 4-3 the percentage of EVs that can be added to the grid in a summer weekday is showed. Lowering the charging power permits to integrate more EVs, and 4 more than a winter weekday, this due to the lower consumption on summer.

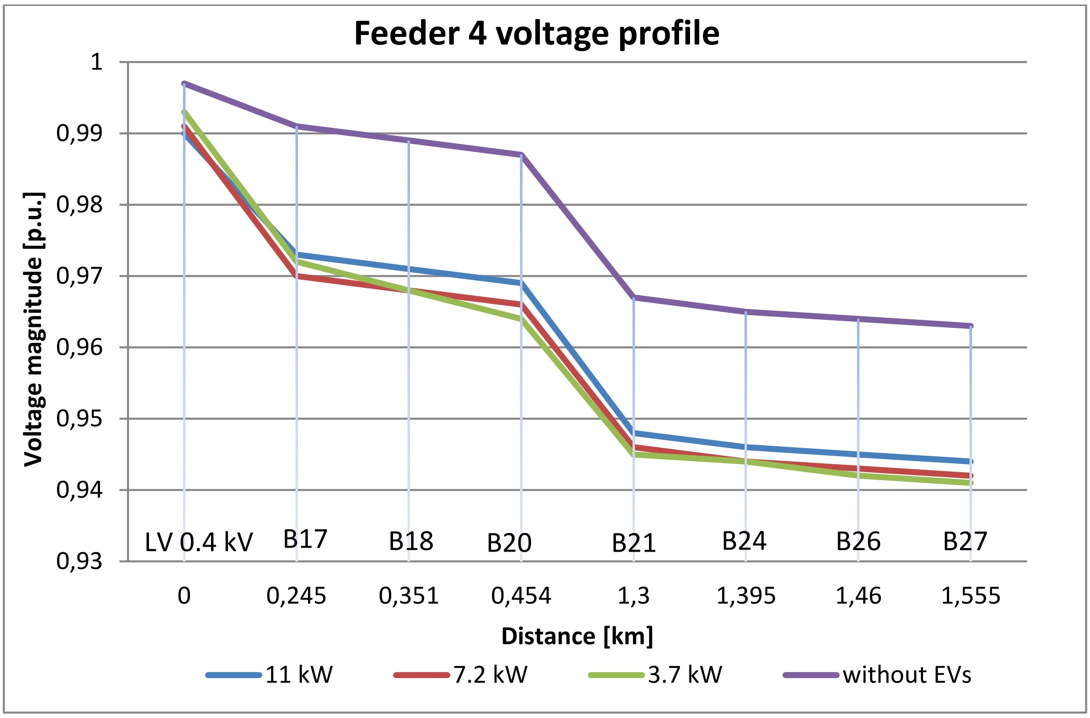


Figure 4-12 Voltage magnitude of Feeder 4 in all cases.

In Figure 4-12, the voltage profile along Feeder 4 is shown. It drastically drops after the EVs are connected to the grid, and it becomes lower with the increasing distance from the main grid. The households which are far from the main busbar will not be able charge their EVs, because of the voltage limit.

4.3.4 Summer weekend

4.3.4.1 Without EVs

The transformer loading peak is slightly lower than the previous case, 44.72 kW (12.12%) from 18:00 to 19:00. This is due to the lack of peak demands in the weekend, as compared to the weekdays where they happen to be more often.
The voltage of the feeders similar as in summer weekday, with Feeder 4 being the most loaded, and bus 27 having the worst voltage of all.

4.3.4.2 With EVs

- 11 kW charging

Table 4-14 11 kW charging of EVs. Summer weekend.

	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Total
Bus number with EVs plugged in	B1, B2, B3, B4	B7, B8, B10, B11, B12	B16	B17	B28	
Number of connected EVs	6	13	1	5	3	28
Number of houses	15	22	1	34	3	75
Percentage of connected EVs	40%	59.09%	100%	14.72%	100%	37.33%

- 7.2 kW charging

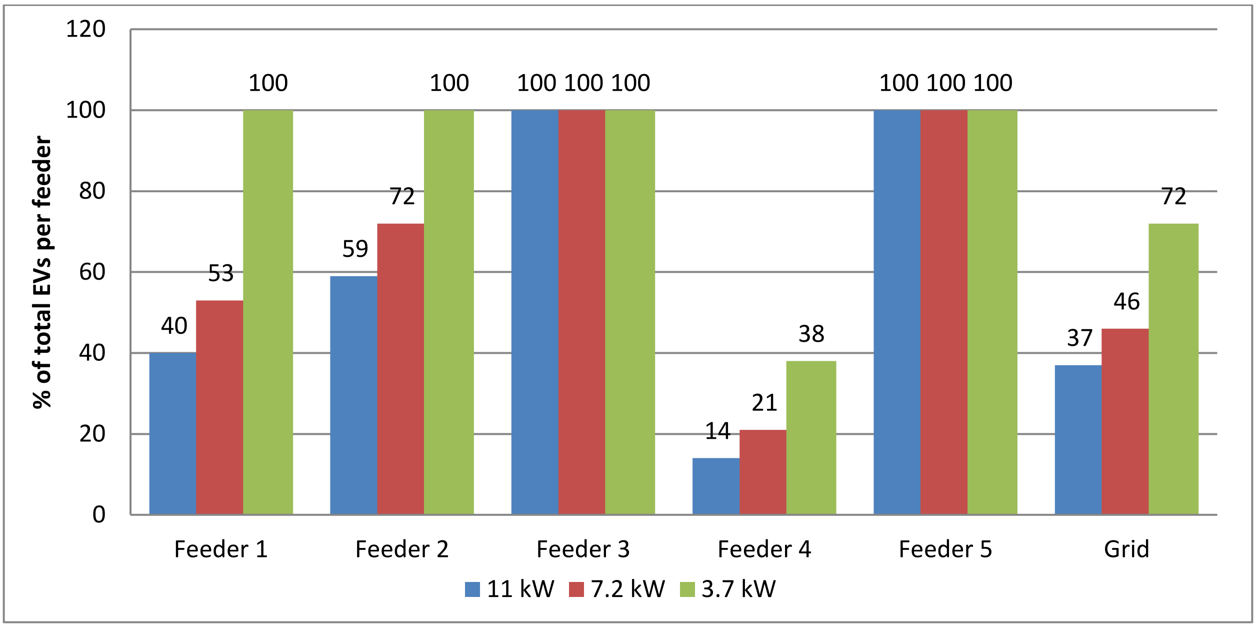
Table 4-15 7.2 kW charging of EVs. Summer weekend.

	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Total
Bus number with EVs plugged in	B1, B2, B3, B4	B7, B8, B10, B11, B12	B16	B17	B28	
Number of connected EVs	8	16	1	7	3	35
Number of houses	15	22	1	34	3	75
Percentage of connected EVs	53%	72.07%	100%	20%	100%	47%

- 3.7 kW charging

Table 4-16 3.7 kW charging of EVs. Summer weekend.

	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Total
Bus number with EVs plugged in	B1, B2, B3, B4	B7, B8, B10, B11, B12	B16	B17	B28	
Number of connected EVs	15	22	1	13	3	54
Number of houses	15	22	1	34	3	75
Percentage of connected EVs	100%	100%	100%	38%	100%	72%

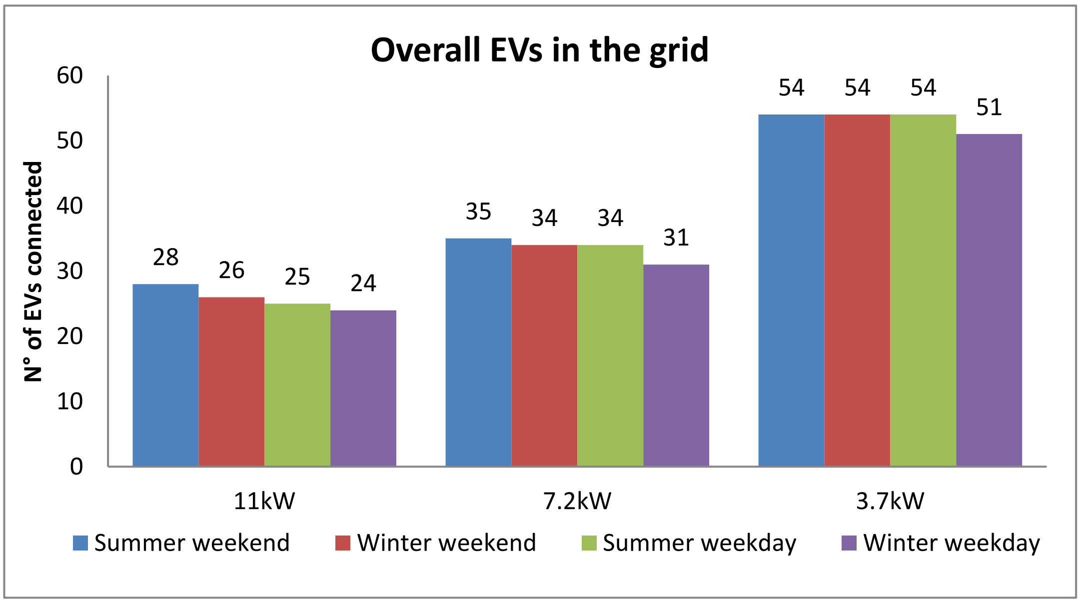


Graph 4-4 Overall comparison of EVs integration in summer weekend.

Comparing the chart from the summer weekday and the one at weekend in Graph 4-4, it can be seen that in the weekend. the number of EVs plugged in is slightly higher.

4.3.5 Summary of the scenarios

Graph 4-5 shows the overall number of EVs that can be plugged-in in each scenario.



Graph 4-5 Overall number of EVs in the grid in each scenario.

It can be observed that in the weekdays of summer and winter, less EVs can be integrated, due to a higher loading demand than in weekends. Still, with the current grid structure and conditions, not all EVs can be intergrated, especially in Feeder 4, which proved to be the weakest in all simulations, and in the best case it could support only 38% of the total possible EVs in the feeder.

4.4 Transformer loading and grid losses

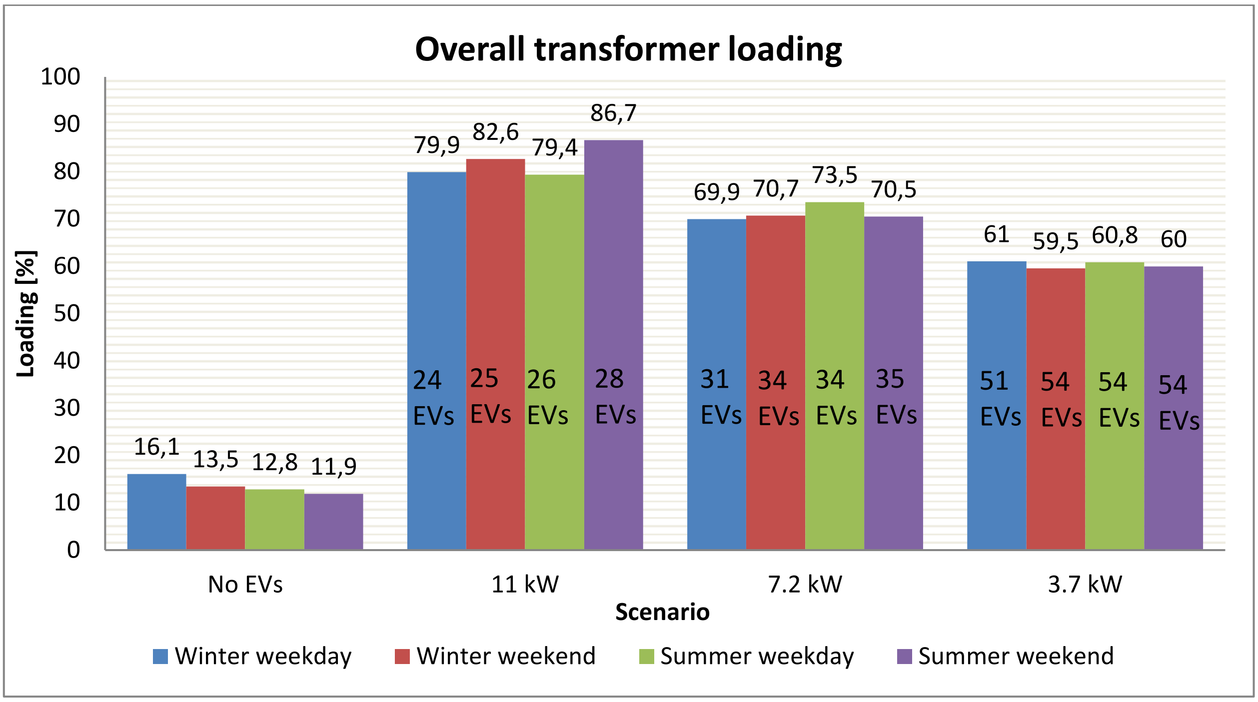
As it is evident, the aggregation of EVs has increased the current flows and, as a result, the losses of the grid have also raised. So, after having simulated the different scenarios, it is necessary to evaluate them. This includes to determine the amount of load that can assume the transformer, which is the device that sets the boundary of their consumption.

In the grid, the transformer has an apparent power of 400kVA. The highest load is in the summer weekend case, in the 11 kW charging scenario, with a peak of 325.95 kW or 86.7% of the transformer. This means that the transformer loading is not the main limitation of the grid.

The overall transformer load and line loss during the simulation is shown on Table 4-17. The line loading is provided in Appendix.

Table 4-17 Overall transformer load and line loss in all scenarios

Scenario		Load [kW]	Load [kvar]	Line loss [kW]	Line loss [kvar]		Scenario		Load [kW]	Load [kvar]	Line loss [kW]	Line loss [kvar]
Winter weekday	No EVs	60.67	15.15	1.81	0.61		Summer weekday	No EVs	48.28	12.06	1.55	0.42
	11 kW	301.38	14.32	12.89	12.24			11 kW	299.44	11.39	12.9	12.2
	7.2 kW	264.61	14.37	11.03	9.68			7.2 kW	277.44	11.37	12.47	10.8
	3.7 kW	231.8	14.42	9.46	7.18			3.7 kW	231.16	11.45	9.51	7.14
Winter weekend	No EVs	50.7	12.67	1.56	0.44		Summer weekend	No EVs	44.72	11.18	1.45	0.35
	11 kW	311.47	11.92	13.55	13.09			11 kW	325.95	10.69	14.63	14.33
	7.2 kW	267.73	10.17	11.04	9.86			7.2 kW	268.03	10.59	10.22	9.1
	3.7 kW	226.43	10.42	9.13	6.83			3.7 kW	228.23	10.61	9.08	6.94



Graph 4-6 Overall transformer loading and no. of EVs plugged-in.

Winter weekday is selected to show the daily transformer loading profile in each scenario, since it is the case which can support less EVs. By lowering the charging power, it can be seen from Figure 4-13 that transformer loading is lower and more EV can be charged.

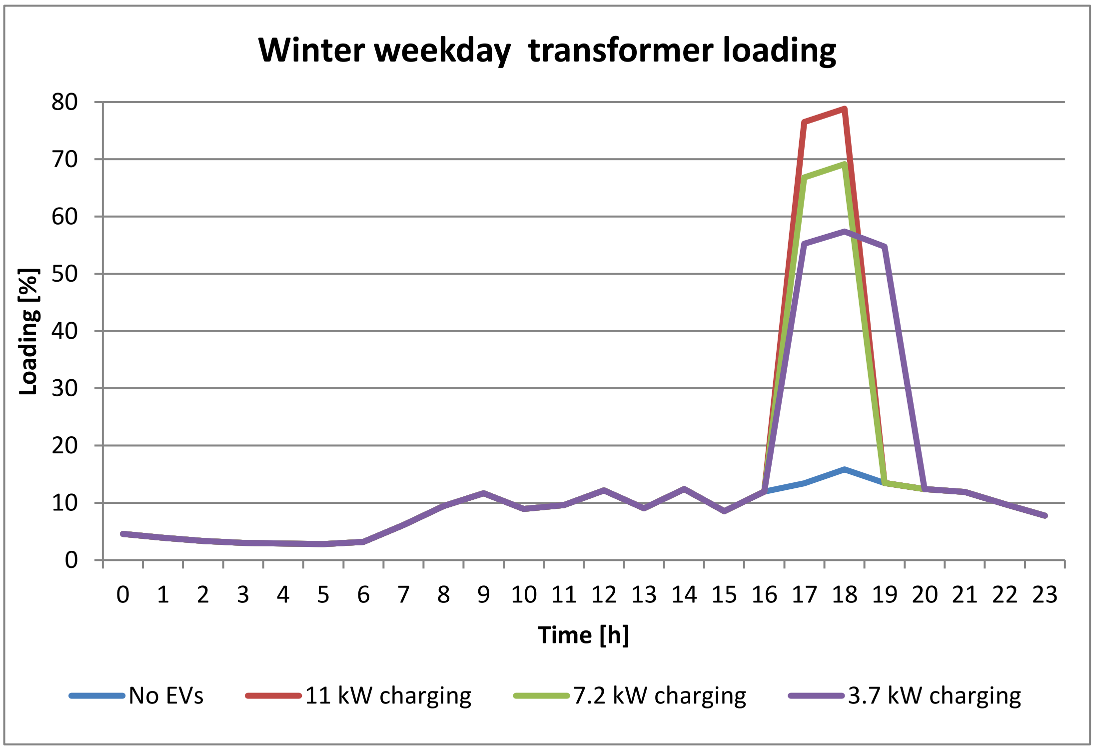
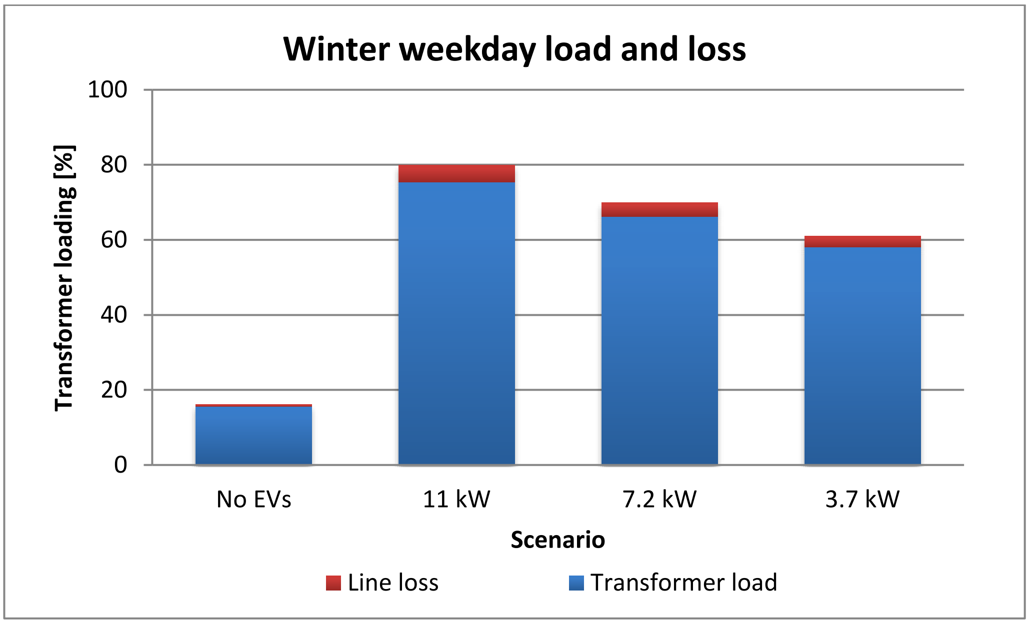
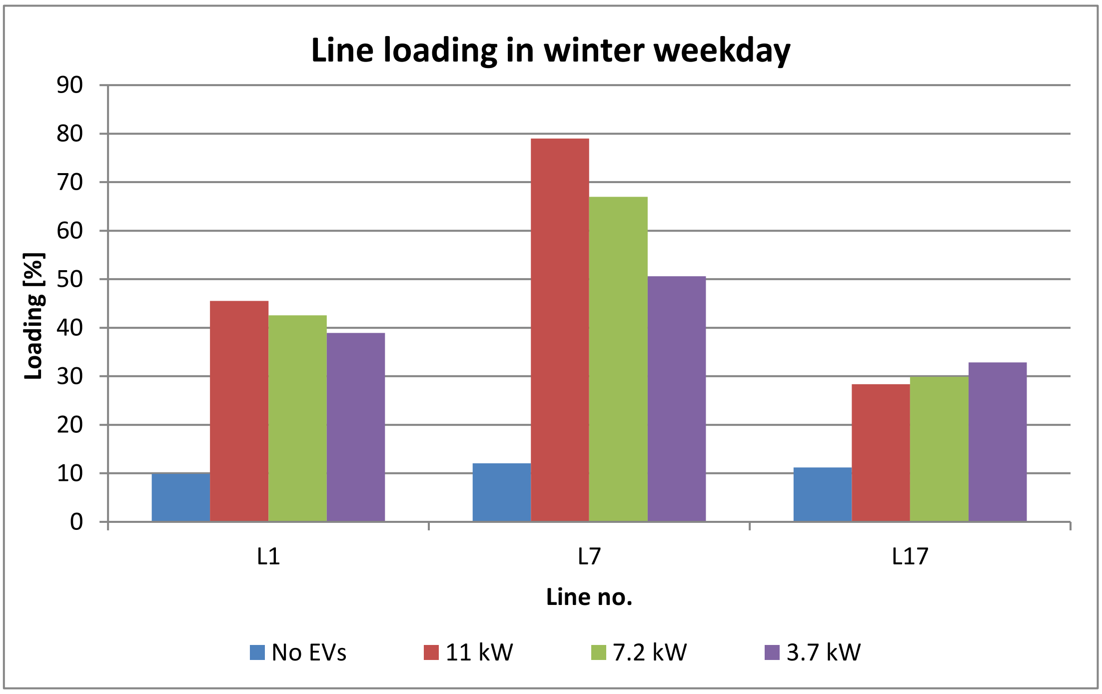


Figure 4-13 Comparison of the daily transformer loading in all scenarios of the winter weekday.



Graph 4-7 Transformer load and loss in winter weekday.

Graph 4-7 shows the comparison of the transformer load and line loss in the grid in different scenarios of a winter weekday. The loading and the voltage limits are fulfilled in all scenarios. The line loss is similar to the other scenarios with different loading, and it is small compared to the total load.



Graph 4-8 Loading of the most critical lines in winter weekday.

The three most loaded lines are shown in Graph 4-8 in all scenarios, during the winter weekday. They correspond to the first line of Feeder 1 (L1), Feeder 2 (L7) and Feeder 4 (L17).

4.5 Conclusion

In this chapter the performance of the grid used in the project was analysed. Initially some verifications were done to see the capability of the grid in supporting EVs. Then 4 scenarios were analysed, in different days of the week and annual periods.

Three different charging powers were chosen to simulate. It was observed that simply by lowering the charging power, more EVs could be plugged-in. But even in the best scenario, the grid could not support all the EVs. The main limiting effect was the voltage magnitude.
Particularily Feeder 4 proved to be the weakest and few EVs could be integrated, mostly nearby the LV busbar.

It can be concluded that with the current grid structure and conditions, not all the households can plug-in their EV, especially those who are far from the main busbar.

To achieve a full EV integration, a smart charging plan will be implemented in next chapter.

5 Implementation of Smart Charging

5.1 Introduction

With the purpose to analyze the functional behavior of the distribution grid with EVs integrated, 4 scenarios were simulated in the previous chapter. In dumb charging mode the grid could support a maximum of 72% of the EVs for the lowest charging power, and 37% of the EVs for the maximal charging power in the best scenarios.

In dumb charging, it was assumed that EVs start charging when they arrive home. This time corresponds to the peak of electricity consumption, therefore it can cause considerable impacts in electric power system operation, such as branch congestions or large voltage drops.

A smart charging methodology is implemented in order to avoid the overloading of the grid, by moving the charging time of the EVs to off-peak time of the electricity consumption. According to the EV smart charging algorithm, the EVs will be charged when the consumption and also the electricity prices are low. Hence, by applying an optimal charging plan, an economical benefit might also be achieved by the EVs owners.

5.2 Objective and methodology of smart charging

The primary objective of the smart charging is to charge all EVs and also minimize the charging cost while satisfying grid constraints. The hourly electricity price is obtained from Energinet.dk, referring to the Elspot price in DKK/MWh.

The charging times are chosen for a period of 17 hours from 15:00 till the next day morning 8:00, which are mainly based on the arriving times in the driving patterns (Charging profiles).

Table 5-1 shows the prices of the hours during a windy winter weekday.

Table 5-1 Elspot price of electricity in a windy winter weekday

Hour	17	18	19	20	21	22	23	24	1	2	3	4	5	6	7
Elspot Price [DKK/kWh]	2,122	2,125	2,124	2,120	2,115	2,113	2,109	2,077	2,120	2,116	2,115	2,116	2,117	2,122	2,127

The methodology used to optimize the cost, shown in Figure 5-1, is explained below:

Step 1: Generate the driving patterns, state of charge, arrival times and charging list of all the EVs.

Step 2: Choose the hour where the price of electricity is the lowest, and check if it is greater than the arrival time of each of the EVs. If yes, plug them at the hour of the lowest price. If not, then move to the next hour of lowest price.

Step 3: Charge the different EVs at 11kW at the hour when the price is low. If the EVs need more than 11 kWh, then keep charging them also at the next lowest price hour.

Step 4: While keeping the voltage limits in the range of 0.94 pu ≤ V ≤ 1.06 pu perform the load flow analysis. Keep adding EVs as long as the voltage limits are satisfied. Once SOC = 100%, plug-out the EV.

Step 5: If in case the voltage limits of any of the buses are not satisfied then add EVs to the next hour with the lowest price. Remove the current charging hour from the list of the available charging hours.

Step 6: Repeat the same procedure for the next EVs until they are all charged.

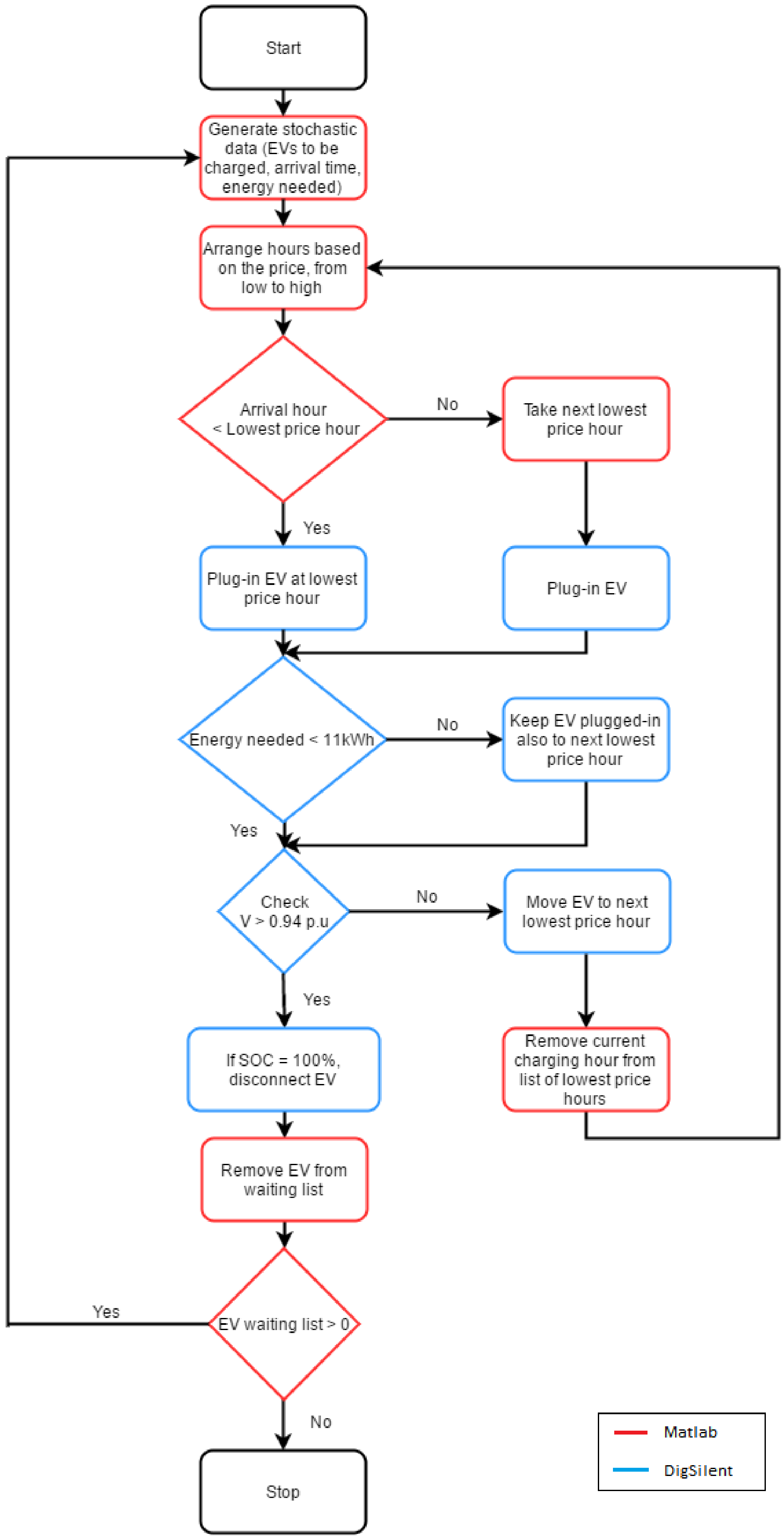


Figure 5-1 Flow chart of EV smart charging

5.3 Simulation of smart charging in winter weekday

In this section the aggregation of EVs will be simulated in smart charging mode, in a weekday in January. The driving patterns and the arriving time of the EVs are taken from section 3.3 (Generation of stochastic data) and the charging price will be based on Table 5-1 considering a windy day. According to the flow chart in Figure 5-1, a smart charging plan is made in Table 5-2. This is the optimal charging time of the EVs in order to minimize the cost and also respecting the grid limits (voltage, loading), which are the same as in dumb charging scenario (Base case analysis).

The simulation is done with 11 kW charging power, to see the capability of the grid in supporting the consumers' needs with the highest charging power and with minimum cost.

Table 5-2 Timetable of the EVs' smart charging

	15 - 16			16 - 17			17 - 18			18 - 19			19 - 20			20 - 21			21 - 22			22 - 23			23 - 00			00 - 01			01 - 02			02 - 03			03 - 04			04 - 05			05 - 06			06 - 07			07 - 08		
No. Evs/ Hour	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60
F1-EV1																												X																							
F1-EV2																												X																							
F1-EV3																												X																							
F1-EV4																												X																							
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F4-EV73		X																																																	
F4-EV74			X																																																
F4-EV75						X																																													
F5-EV1																								X																											
F5-EV2																								X																											
F5-EV3																								X																											

Table 5-2 shows the smart charging schedule of the EVs during a day. The charging period of time needed to fully charge a vehicle was marked with an "X", varying from 20 minutes to 120 minutes, according to the driving patterns.

It can be observed that in smart charging the majority of EVs charge during the lowest price hour, from 00:00-01:00. (Table 5-1). This not only reduces the cost, but also shifts the charging to the off-peak demand hours, so more EVs can be charged according to (The smart charging) in Chapter 2. Now the grid can charge all the 75 EVs.

5.4 Analysis of the results

In this section, the results of the simulation are going to be discussed.

Figure 5-2 shows a comparison of the busbars voltage profile of the grid in the peak hour of the 2 scenarios, with maximum EVs in dumb charging and smart charging.

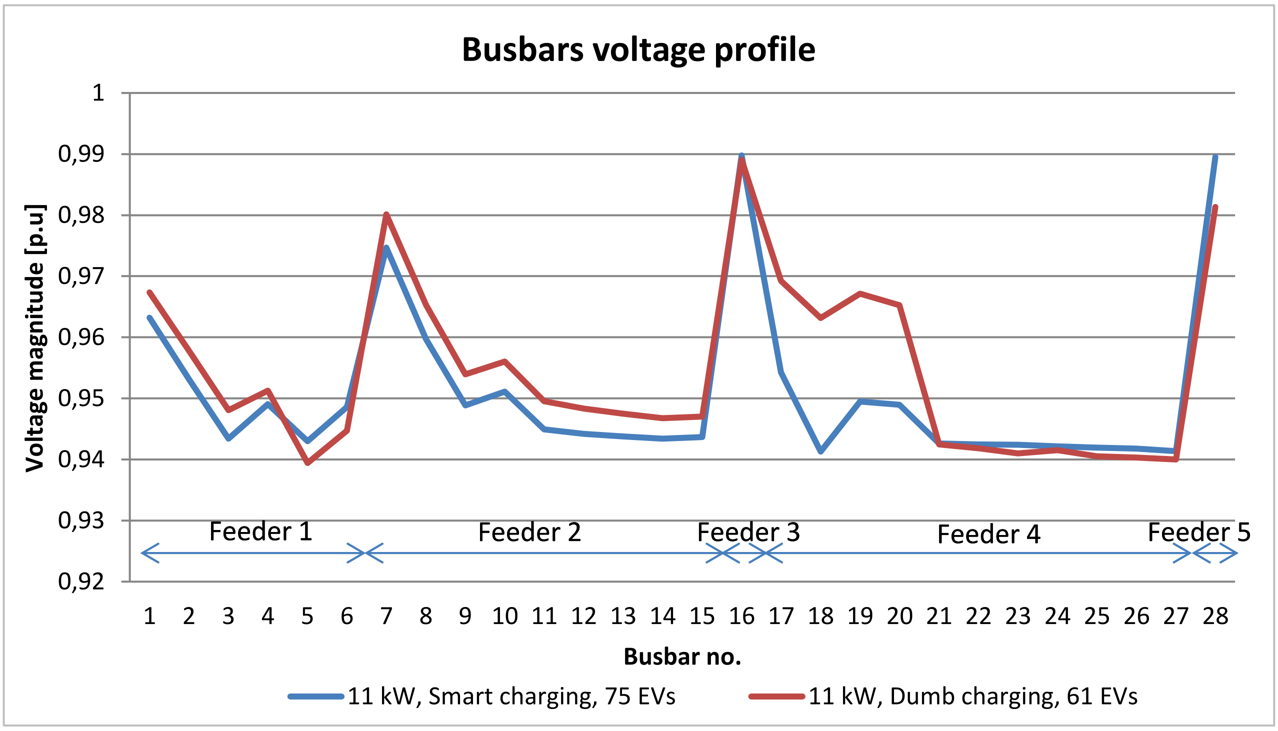


Figure 5-2 Busbars voltage profile comparison: Smart charging at 00:00-01:00 vs. Dumb charging at 17:00-18:00.

It can be observed that the voltage magnitude of the busbars in the peak hour of smart charging is similar to the dumb charging. But in this case all EVs are charging, instead of 61 in the previous case.

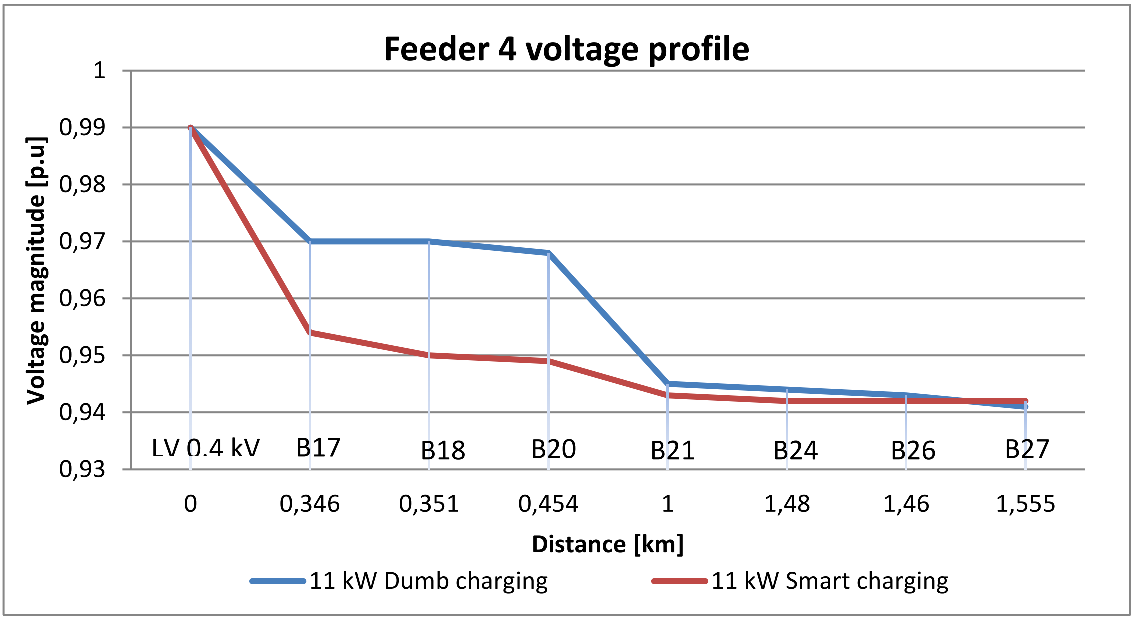


Figure 5-3 Feeder 4 voltage profile comparison: Smart charging at 00:00-01:00 vs. Dumb charging at 17:00-18:00.

In Figure 5-3 it can be seen that Feeder 4 is more uniformely loaded in the smart charging scenario. This is because there is a total of 14 EVs charging distributed along all busbars, while in dumb charging, there were only 5 EVs in Busbars 17 and 18.

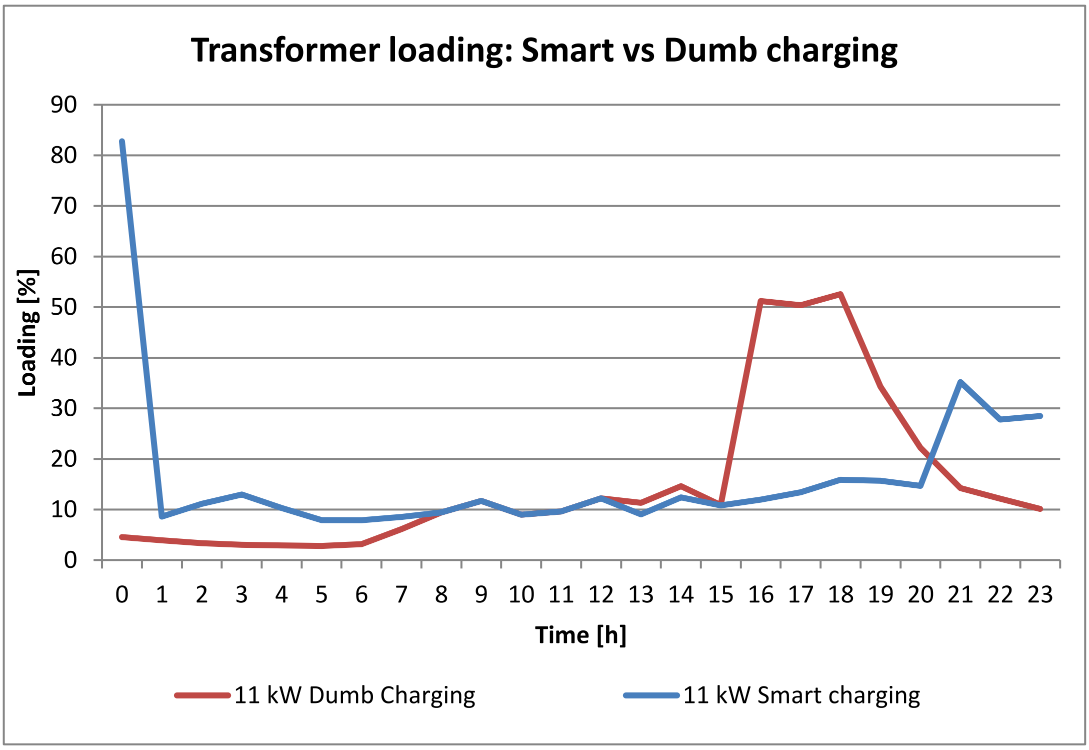
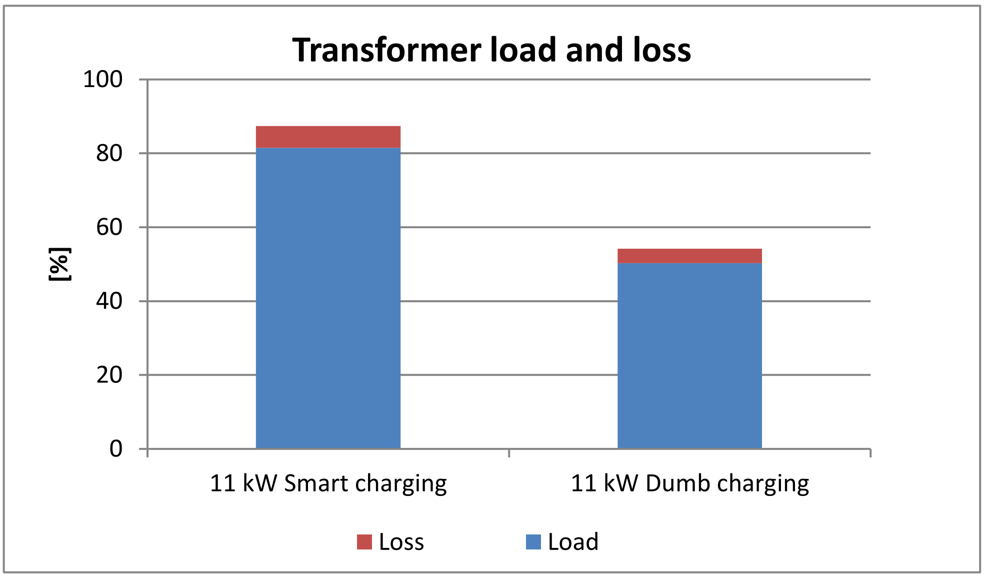


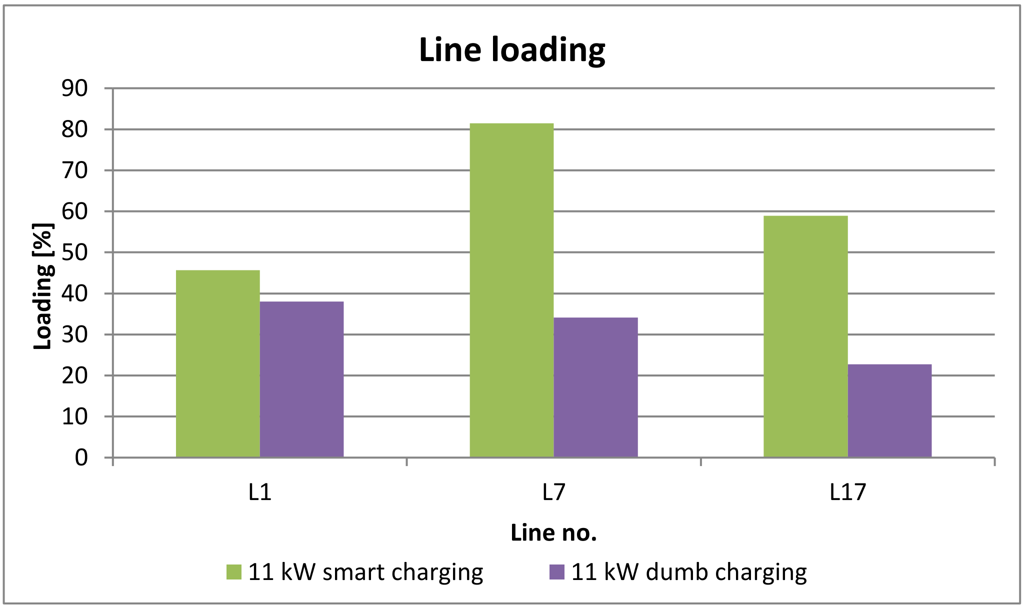
Figure 5-4 Transformer loading in smart charging and dumb charging.

From Figure 5-4 it can be seen that in smart charging the peak load of the transformer is shifted during the lowest price hours and its higher due to a larger no. of EVs. In both cases the transformer rating is not exceeded.



Graph 5-1 Transformer load and loss: Smart charging vs. dumb charging in the peak hour.

The load and loss of the transformer are shown in Graph 5-1. The load is higher than the dumb charging scenario, but all EVs are charged in this case, instead of 61 in the previous one. The loss/load ratio is similar in both cases.



Graph 5-2. Loading of the most critical lines in smart and dumb charging.

The three most loaded lines during smart charging are shown in (Graph 5-2), compared with dumb charging. They correspond to the first line of Feeder 1 (L1), Feeder 2 (L7) and Feeder 4 (L17). There's a higher loading due to larger no. of EVs charging, but the line capacity is not exceeded.

5.5 The optimized charging cost

The main objective of the smart charging is to charge all EVs without violating the grid constraints and also optimize their charging cost. In dumb charging (Winter weekday) EVs start charging as soon as they arrive home. The cost of this charging is compared with the one in the smart charging plan.

The electricity price considered for the calculation is the one in Table 5-1.
The total cost in the smart charging scenario can be calculated with the formula below:

$$C_S = \sum_{n=1}^{17} (c_n \cdot \sum_{m=1}^{75} E_m) = 1397.1\ DKK \quad (4)$$

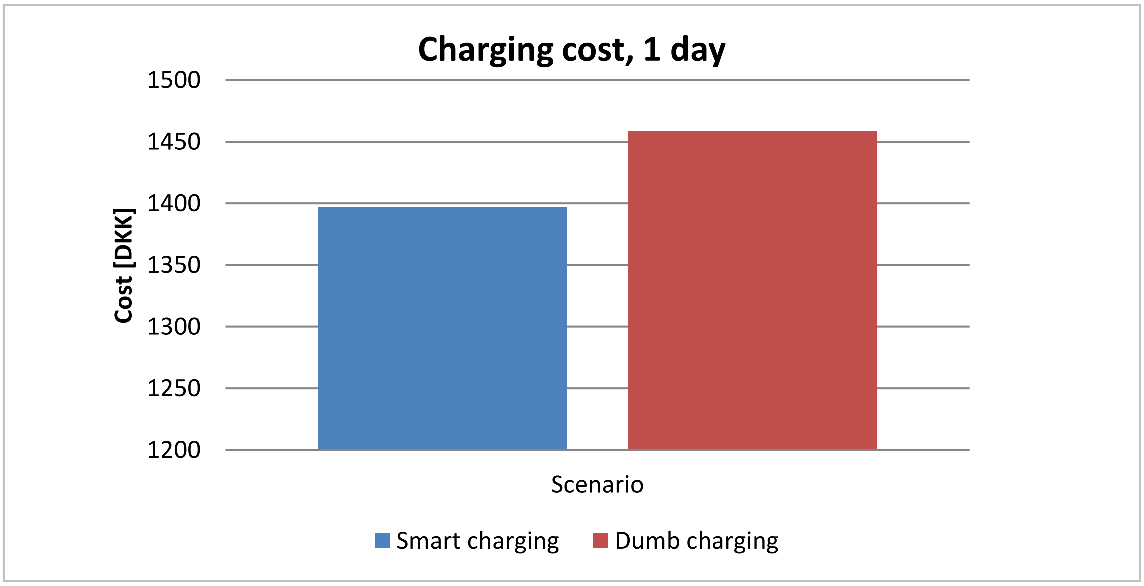
While the dumb charging cost is:

$$C_D = \sum_{n=1}^{24} (c_n \cdot \sum_{m=1}^{75} E_m) = 1459.1\ DKK \quad (5)$$

By implementing the smart charging plan, the reduction of the cost in one day is:

$$C_D - C_S = 1459.1 - 1397.1 = 62\ DKK \quad (6)$$

In Graph 5-3 it is shown the comparison of the daily charging cost between the two scenarios.



Graph 5-3. Comparison of the charging cost of 75 EVs for one day.

The total cost of the two charging scenarios for 1 year is:

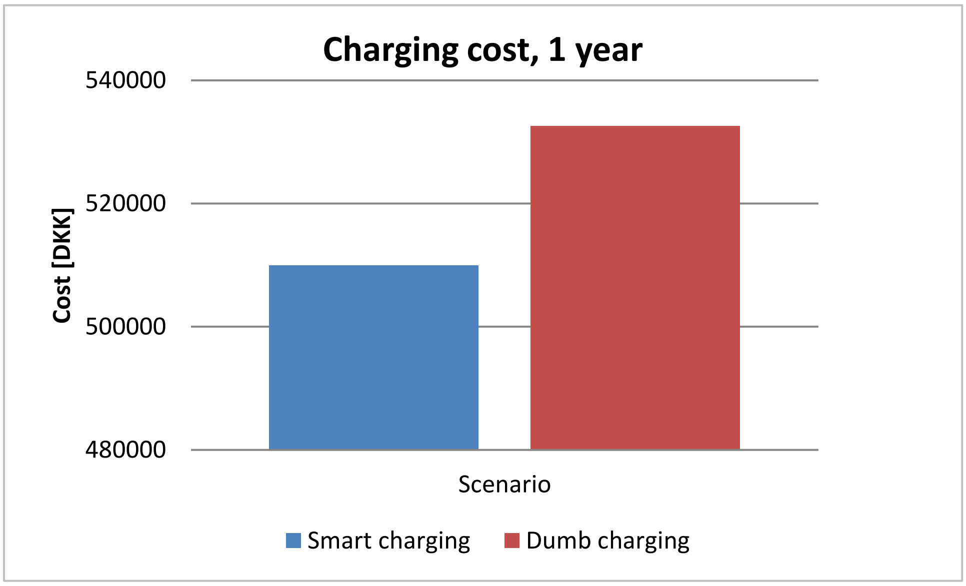
$$C_{SA} = C_S \cdot 365 = 532571.5\ DKK \tag{7}$$

$$C_{DA} = C_D \cdot 365 = 509941.5\ DKK \tag{8}$$

The total reduction of the annual cost is:

$$C_{DA} - C_{SA} = 532571.5 - 509941.5 = 22630\ DKK\ (3041\ €) \tag{9}$$

Based on these calculations, by implementing the smart charging plan the 75 EV owners can reduce their cost by approximately 22630 DKK. (Graph 5-4)



Graph 5-4. Comparison of the charging cost of 75 EVs for one year.

5.6 EV revenues from participation in V2G

Regulation and manual reserves are the mandatory ancillary services required in any power system for a reliable operation [49]. Various studies have reported that V2G is best suited to provide these services [36], [50].

The regulation service is the automatic generation control which tunes the power system voltage and frequency to satisfy the energy balance, and it can be up or down, depending on the demand.

The process occurs many times a day and it requires a fast response from V2G (less than a minute) and may last only for a few minutes. For these services the EVs are paid a fixed cost (capacity cost) for their power rating based on the time they are available. There is also a variable cost for the actual energy supplied during the regulation or the reserve operation.

In Table 5-3 it is shown the reserve capacity and power requirements in Western Denmark and the energy costs.

Table 5-3 Reserve power capacities and costs [7]

Ancillary services	Reserve power requirement	Average capacity cost	Average energy cost
Regulation	+/- 140 MW (15 minutes)	100,000/MW per month	100 DKK/MWh
Manual reserves	+520 MW/-160 MW (1-3 hours)	50,000/MW per month	420 DKK/MWh

1 euro = 7.45 Danish kroner (DKK)

A similar EV to the Tesla model S providing ancillary services could possibly get a considerable annual payment to the owner, as shown in Table 5-4. It can be observed that the earnings from the regulation services are higher than those for manual reserves. This because the regulation services are used many times during the day to cope with the grid fluctuations and so are offered a higher price.

The total earnings from the EVs depend on hourly market prices, total plugin time, state of charge, and power line capacity. The calculations are based assuming that EVs are plugged-in 20 hours a day, with a 10% daily utilization for regulation and referring to the costs in Table 1. The revenue is higher for the 20 kW power line connection.
The ancillary services supplied by the EVs will be a mix of a large number of small different units. Aggregate models of storage units are considered to analyse their performance in the power system; this will reduce computation time of the simulation and the overall complexity.

Table 5-4 V2G ancillary service payments [7]

Ancillary services	Power line capacity	Possible annual payment from V2G services		
		Capacity [DKK]	Energy [DKK]	Total [DKK]
Regulation	15 kW	15330	1095	16425
	20 kW	20440	1460	21900
Manual reserves	15 kW	7655	126	7791
	20 kW	10220	168	10388

5.6.1 Renewable energy support from V2G

- PV support

In this section the V2G technology is analysed to support large scale integration of renewables like photovoltaic (PV) and wind power.
V2G could support grid-solar PV integration by storing power during the production peak and supply it to the grid on peak demand. It is estimated that in 2024 the installed capacity of PV will be approximately 1.14 GW [51]. Assuming a line capacity of 15 kW, then this capacity has to be supported by 76000 EVs. This is equivalent to approximately 3.2% of the current vehicle fleet available in Denmark. If only half of these vehicles are requested for on-demand support, the V2G power contract must include 6.4% of the vehicle fleet.

- Wind Power support

Taking into account the utilisation of the Danish power utility to be 50% of the installed electric capacity of 14.05 GW, to generate half of it from wind power, which has a capacity factor of 35%, 10.03 GW of wind power is needed. Assuming the requirement of the regulation service 6% of the wind capacity, 602 MW have to be supported by the V2G. If power line capacity is assumed 15 kW, 40120 EVs are needed, which is equivalent to 1.67% of the current vehicle fleet in Denmark. Considering half of the EVs available on demand, 3.35% of the total vehicles have to be offered the V2G contract.

Table 5-5 V2G support for PV and wind power

Renewable Power	Application	Capacity [GW]	V2G support type	V2G support needed	V2G availability	% of current vehicle fleet
Solar PV	Peak load (10%)	1.14	Dedicated storage (1 hour)	1.14 [GW]	50%	6.4%
Wind	Base load (50%)	10.03	Regulation (15 min.)	0.557 [GW]	50%	3.35%
			Manual reserves (1 hour)	1.02 [GW]	50%	6.2%

Considering that the equivalent of 11% of wind power capacity is needed for the manual reserve of the power system, 73554 EVs (3.1% of the total fleet) are needed to support 1.1 GW. If only half of the vehicles are made available for the manual reserves, 6.2% of the fleet need to be contracted.

From Table 5-5 it can be observed that with EVs less than 7% of the total vehicle fleet in Denmark, V2G can provide a considerable support to the ancillary services for 50% of electricity production from renewables like PV and wind power, to the power system. In the coming years, less EVs could be implemented into V2G to provide ancillary services for large integration of renewable energy, since it is expected that the power capacity of the EVs will increase with the development of high storage batteries.

5.7 Conclusion

The smart charging has been simulated in this chapter, in order to charge more EVs than in dumb charging while respecting grid limits.

The price of electricity depends on the wind power production and the consumption demand.
A windy winter weekday was chosen to make the simulation, and all EVs could charge during 15.00 – 08.00 instead of only 61 in the 11 kW dumb charging scenario.

Also the charging cost is optimized, and some savings can be appreciated in the annual cost.
If the EV owners participate in V2G contract, they would get significant incomes, especially when providing regulation services.

6 Survey: assesment on the transition from ICE cars to EV/HEV at PoliTO

6.1 Introduction

This survey has been carried on from October 2016 – February 2017 and is part of the initiatives proposed within the activity of Mobility Management at the Politecnico di Torino. It aims to assess the actions that the University can take in order to facilitate the possible spread of plug-in hybrid or electric cars among the staff as service vehicles, or as alternatives to internal combustion vehicles (ICE). In this context it will be possible to assess as well the installation of some charging stations inside the Politecnico di Torino, for potential purchases of electric or plug-in hybrid vehicles.

6.2 Objectives

- Understand the benefits of electric & hybrid cars and facilitate their spread
- Quantify:
  - the actual annual economic savings at user level
  - the years needed to recover the initial cost of switching to an electric / hybrid car
- Define the most cost-effective solution for buying an electric, hybrid or plug-in hybrid car according to each user's driving pattern
- Evaluate the installation of the charging stations inside the university

6.3 Processing of information

In the following there is the elaboration of the data provided from the answers to the survey, by one of the University staff members.

The comparison between the present ICE car of the user and the hybrid/electric one is made by quantifying both the energy, economic and environmental savings (CO_2) produced by the change, and also the number of years needed to recover the difference between the initial purchase cost of the new chosen car with respect to the actual one.

The input data needed for the evaluation were obtained from the survey answer and with the support of external sources, in particular[1]:

 Oil Union, based on data from the Ministry of Economic Development (MiSE), which supplies fuel prices

 Electricity and Gas Authorities, which provide data on the cost of electricity

 Quattroruote and *Greenstart*, which provide the specifications for each car model

[1] The data from external sources is referred to the period of the answer to the survey

6.3.1 Quantification of the average annual mileage

In Table 6-1, the average annual mileage of the user is reported, based on the data provided in response to the survey.

Table 6-1 Average annual kms of the user (Source: Survey on staff mobility)

Average annual mileage of the user					
Type of displacement	**Reason of displacement**	**Daily mileage** [km]	**N° of displacements** [days/year]	**Average annual mileage** [km/year]	
Urban	Work	65[2]	200		13000
Extraurban	Weekend	200	52	10400	10500
	Holidays	100	1	100	
Total					**23500**

<u>The user declares to travel with the same ICE car 23.500 [km/year] on average.</u>

6.3.2 Quantification of the annual consumptions and CO_2 emissions

Table 6-2 shows the prices for fuels and electricity.

Table 6-2 Prices of the fuel and electric energy (Source: MISE & Authorities for electric energy and gas)

Fuel & electricity price						
Gasoline price (€/litre)	**Diesel price** (€/litre)	**GPL price** (€/litre)	**Methane price** (€/litre)	**Electricity price**[3] [c€/kWh]	**Excise taxes**	
					Erarial tax (c€/kWh)	**VAT** (%)
1.502	1.351	0.56	0.973	18.27	2.27	10

- <u>ICE car</u>

The specs of the user's ICE car are shown in Table 6-3, along with the annual consumptions and cost in Table 6-4.

[2] Eventhough provided by real data of the user's journey, it might not represent the typical average journey of the all users, as the average daily mileage range from the survey is 10-30 [km].

[3] Approximative cost on the period of analysis

Table 6-3 Specs of the user's ICE car (Source: Survey on staff mobility)

ICE car specifications						
Car model	Fuel	CO_2 emissions [g/km]	Price [€]	Consumption [l/100 km]		
				Urban	Extraurban	Mixed
Mini Cooper D	Diesel	92	28000	3.5	4	3.5

Table 6-4 Annual consumptions and cost of the ICE car

Annual energy consumptions, emissions & cost					
Fuel type	Annual average mileage [km]	Fuel consumption [l/year]	Energy consumption [tep/year]	Annual CO_2 emission [ton/year]	Annual supply cost [€/year]
Combustion	23500	875,00	0.92	2.16	1182.13

- Electric/Hybrid car

The user-identified car is the BMW 225XE, plug-in hybrid. Car specifications are shown in Table 6-5.

Table 6-5 Specs of the hybrid car identified by the user

Specifications of the plug-in hybrid car								
Car model	Fuel	Electric range [km]	Battery [kWh]	Electric consumption [kWh/km]	CO_2 emission [g/km]	Price [€]	Consumtion [l/100 km]	
							Urban	Extraurban
BMW 225 XE	Gasoline/Electric (Hybrid)	40	5	0,118	46	38400	2.2	1.8

In Table 6-6 the annual consumptions, CO_2 emission and cost of the identified car are shown.

Table 6-6 Annual consumptions, emissions and cost of the plug-in hybrid car

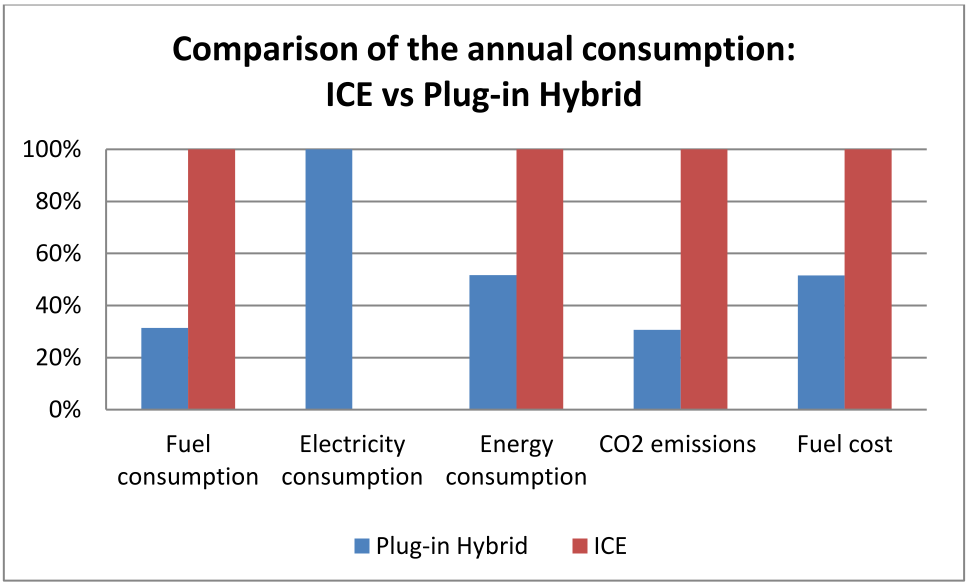
Annual energy consumptions, emissions & cost						
Fuel type	Annual average mileage [km]	Fuel consumption [l/year]	Electricity consumption [kWh/year]	Energy consumption [tep/year]	Annual CO_2 emission [ton/year]	Annual supply cost [€/year]
Plug-in hybrid	23500	274.80	1073.80	0.48	0.66	608.93

6.3.3 Comparison ICE vs. Plug-in Hybrid

Table 6-7 and Graph 6-1 show the average differences of the annual energy consumption, emissions and fueling costs between the user's current car and the plug-in hybrid car chosen.

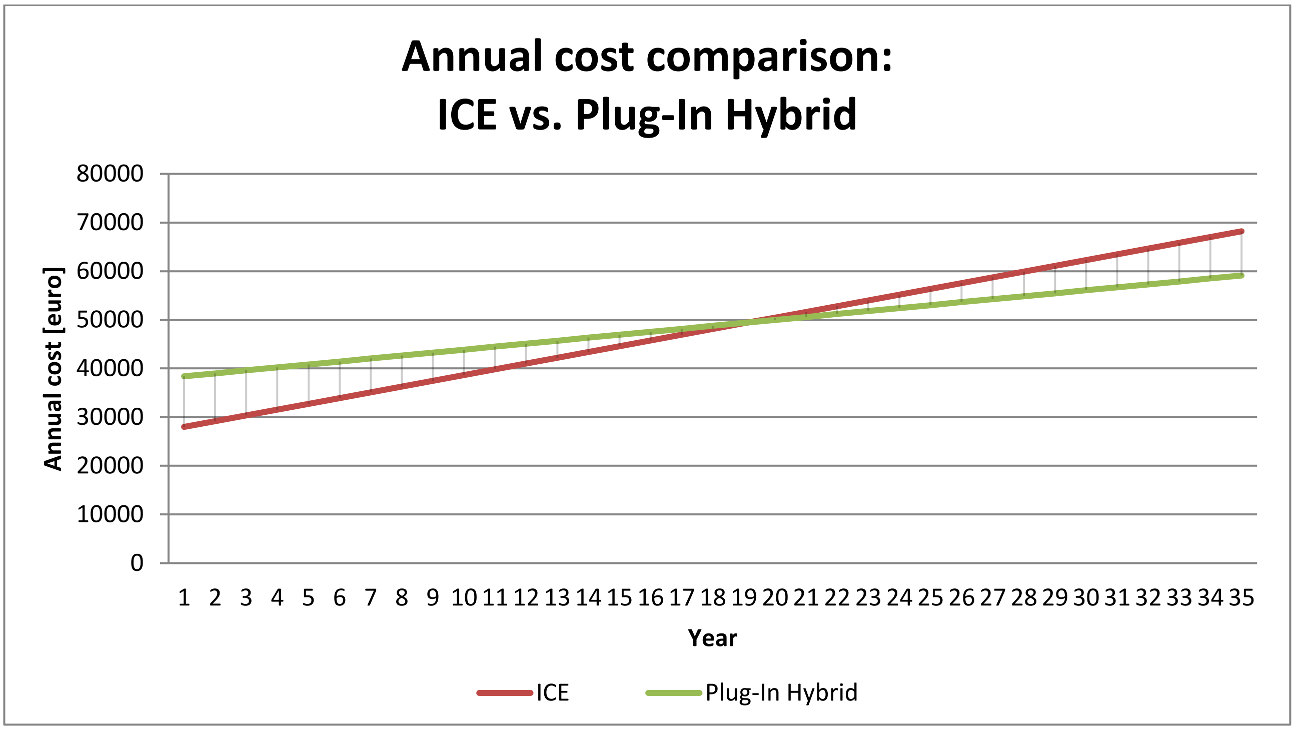
Table 6-7 Comparison of the annual consumptions and cost ICE vs. Plug-in Hybrid

Differences of the annual consumptions, emission & cost					
Car model	**Fuel consumption** [l/year]	**Electricity consumption** [kWh/year]	**Energy consumption** [tep/year]	**Annual CO_2 emission** [ton/year]	**Annual supply cost** [€/year]
Auto a combustione vs. Ibrida Plug-In	-600.2	+1073.80	-0.44	-1.50	-573.19



Graph 6-1 Difference in % of the annual consumptions, emissions and cost ICE vs. Plug-in Hybrid

Based on the results obtained and the purchase cost of the analysed cars, it can be quantified the number of necessary years to recover the difference of the initial purchase cost, by taking into account only the costs linked to the annual consumptions (excluding maintenance costs).



Graph 6-2 Comparison of the annual consumption ICE vs. Plug-in Hybrid

Considering a constant average annual mileage and consumptions, switching to the selected hybrid car is economically non profitable in this case. This is due to the big initial cost difference of the plug-in hybrid compared to the current car (Graph 6-2).

It can be said that the proposed action, despite allowing to reduce energy consumption, CO_2 emissions in the atmosphere and the annual cost of supply to the user, it turns out that in absence of significant economic incentives (government and non), is difficult to implement since the number of years needed to recover the initial expenditure is much higher than the average life of a car (for ex. 10 years), by the time at which the user should at least equalize the initial investment.

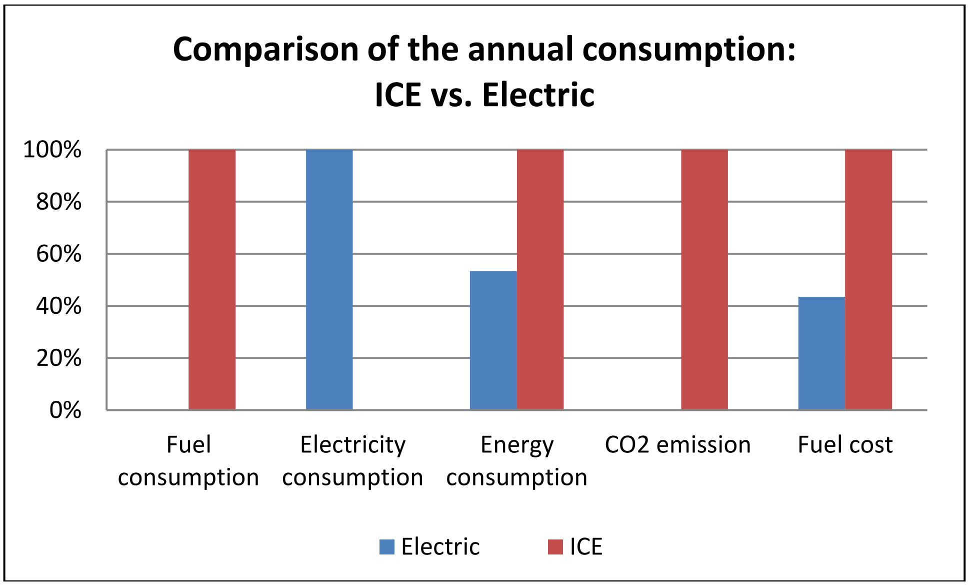
6.3.4 Electric car proposal

Based on the preferences expressed in the survey, the user is willing to pay 10-30% more for a hybrid/electric car than the conventional one with a combustion engine. Taking into account the types of journeys that are typically carried out, an alternative is proposed - obviously only on the basis of energy criteria - which has the following characteristics, as shown in Table 6-8.

Table 6-8 Specifications of the proposed electric car (Source: Quattroruote)

Specifications of the electric car								
Car model	**Fuel**	**Electric range** [km]	**Battery** [kWh]	**Electricity consumption** [kWh/km]	**CO_2 emission** [g/km]	**Price** [€]	**Consumption** [l/100 km]	
							Urban	**Extraurban**
Hidden but existing[4]	Electric	200	24	0.12	0	29810	0	0

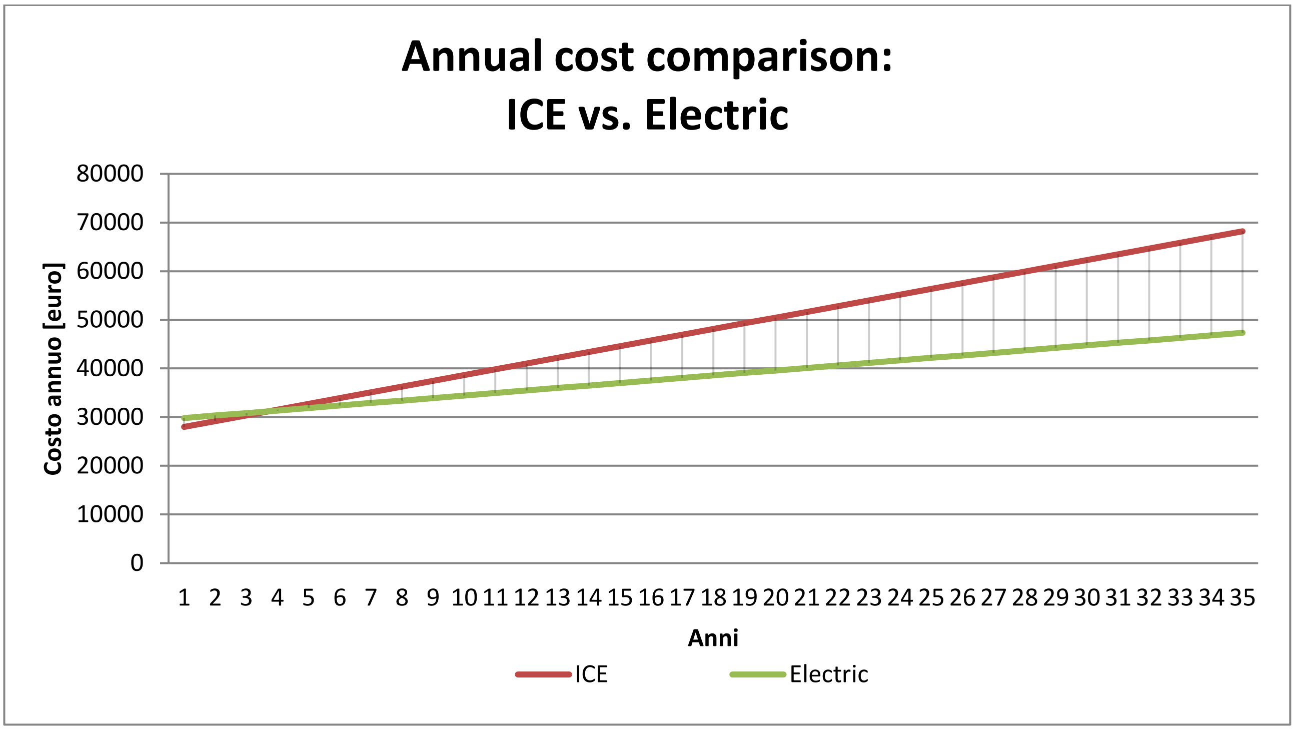
Graph 6-3 shows the average differences in annual energy consumption, emissions and fuel cost between the proposed electrical car and the actual one.



Graph 6-3 Difference in % of the annual consumptions, emission and cost ICE vs. Electric

Based on the results obtained and the purchase cost of the analysed cars, it can be quantified the number of years needed to recover the difference in the purchase cost based only on the costs related to the annual energy consumption (excluding maintenance costs).

[4] Specs from quattroruote.it for an actual car model on the market



Graph 6-4 Comparison of the annual consumption ICE vs. Electric

6.4 Results

Considering that average annual journeys and annual energy consumption remain constant, due to an initial purchase cost difference of -2500 € between the proposed electric car and the ICE car, at the 4th year (Graph 6-4) there is a drawback of the costs. Therefore, at the end of the useful life of the vehicle, the user will gain an additional economic advantage that in the 10th year is quantified at +4192 €. This emerges without considering maintenance costs, stamp duty / state subsidies. Also, switching to the electric car, helps to clear the CO_2 emissions.
Another advantage is the possibility to use the charging spots that the University is considering to install.
The action proposed by the Mobility Management is therefore very likely to be successful, as the energy and environmental benefits previously quantified are accompanied by a major economic benefit to the user.

6.5 Evaluation of charging columns inside the university

As proved from the survey results, switching to an electric/hybrid vehicle has many advantages: environmental, economic, less maintenance, more silent and comfortable ride etc.
Yet, the biggest limitation (besides the higher cost) is the battery range and charging time. Also there's still a gap in the charging infrastructure, where there's still much to do in terms of charging stations along the national territory. This means that in case of a long journey (more than 50-100 km), the driver has to consider the residual battery range and adapt its route to the availability of the charging stations, which in case of an ICE car would not be an issue.

To make the EV mobility more feasible, Politecnico di Torino is considering to install some charging columns inside its parking areas.

6.5.1 Energy needs

Based on the survey data (Figure 6-1):

- only 21% of the users with a positive result opted for an electric or plug-in hybrid car (which can take advantage of the charging station)

- this emerges from the fact that the initial cost of these cars is still restrictive in order to appreciate long-term economic savings compared to the same class ICE cars

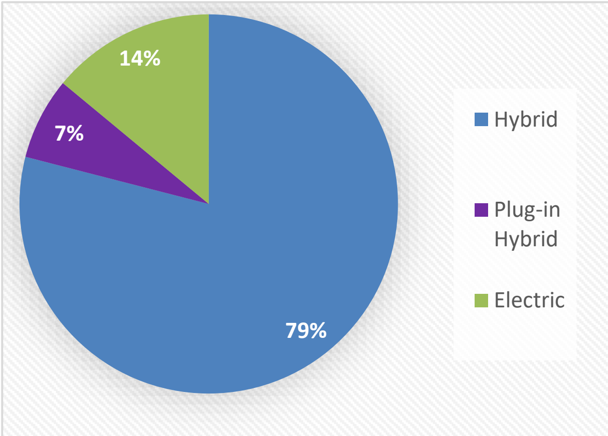


Figure 6-1 Distribution in % of the users who had a profitable switch from the ICE car

Among users willing to switch to an electric/hybrid car:

- 14% chose an EV
  - average journey on working days 51.25 [km]
  - average energy consumption 0.12 [kWh/km]
    - ➢ Average energy needed for the daily journey is 6.15 kWh

- 7% chose a PHEV
  - average journey on working days 50 [km]
  - average energy consumption 0.16 [kWh/km]
    - ➢ Average energy needed for the daily journey is 8 kWh

With slow charging (2.2 – 3.6 kW), these users should remain connected to charging stations for:

- 2 - 3 hours for the electric car
- 2.5 – 4 hours for the plug-in hybrid car

in order to fullfill the energy needs for the daily journeys.

6.5.2 Charging scenario

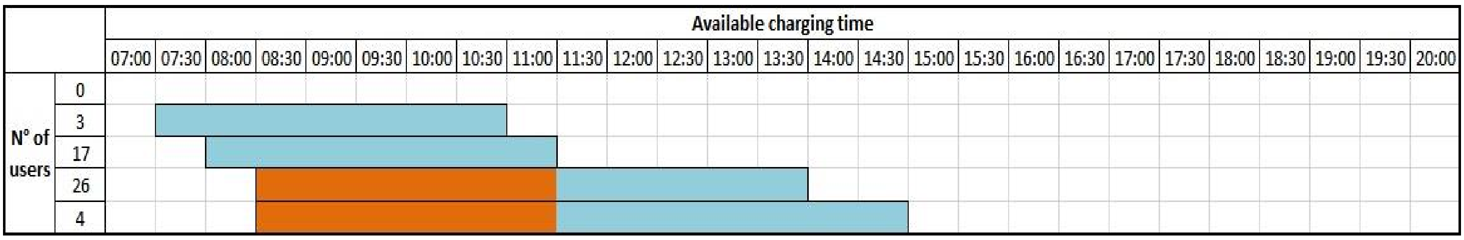
An optimistic scenario could be installing 20 charging columns distributed inside the parking areas of the Politecnico and 50 EV/PHEV owners who charge their cars daily. From the survey data, users come at work between 07^{15} – 08^{30} and leave between 18^{15} – 19^{40}, so charging availability of the columns from 07^{00} - 20^{00} could be planned. Each column can support 2 users at the same time, with slow charging (3.6 kW max).
Two charging scenarios can be implemented:

- *Uncontrolled charging* - the users charge their car whenever they want, based on the arriving times and the column availability
- *Controlled charging* – the users reserve their charging spot with an App, which schedules the bookings in order to avoid peaks of charging load and those from the university grid during the day

6.5.2.1 Uncontrolled charging

As soon as the users reach University, they plug-in their EV/PHEV for 2-4 hours, to obtain enough charge for the daily journey. In Table 6-9 it is shown the time of arrival of the users and the connection to the charging spots. Not all of them can plug-in as soon as they arrive, because the column capacity is reached at 8^{30} ; the remaining ones will plug-in when the columns are freed.

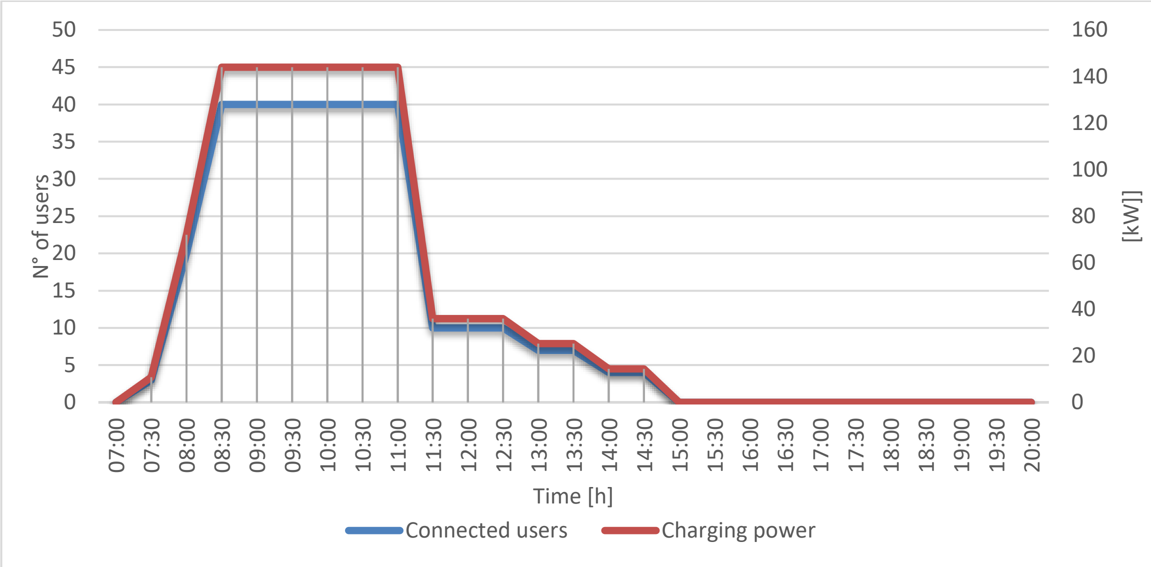
Table 6-9 Scheduling of the uncontrolled charging



So at 8.30, when all the columns are full, the max charging load will be:

$$P_{peak} = 2 * 20 * 3.6 = 144 \text{ kW}$$

As shown in Graph 6-5, the charging load is not distributed equally during the day, but there's a peak in the morning hours when the users reach the University, while in the afternoon there's almost no one charging. This might compromise the grid stability as it might not be able to provide the charging power for all the users.



Graph 6-5 Distributon of the connected users and the charging load during the day – Uncontrolled charging

6.5.2.2 Controlled charging

After the users reach the University, they check the App for free spots and book a charging spot, based on the App suggestion. The App will allocate each booking in one of the 20 columns during the available charging hours (7^{00} – 20^{00}) and will try to distribute equally the charging power during the day, while also fulfilling the users' energy needs.

Table 6-10 Scheduling of the controlled charging

		Available charging time																										
		07:00	07:30	08:00	08:30	09:00	09:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30	16:00	16:30	17:00	17:30	18:00	18:30	19:00	19:30	20:00
N° of connected users	0																											
	2																											
	4																											
	4																											
	4																											
	4																											
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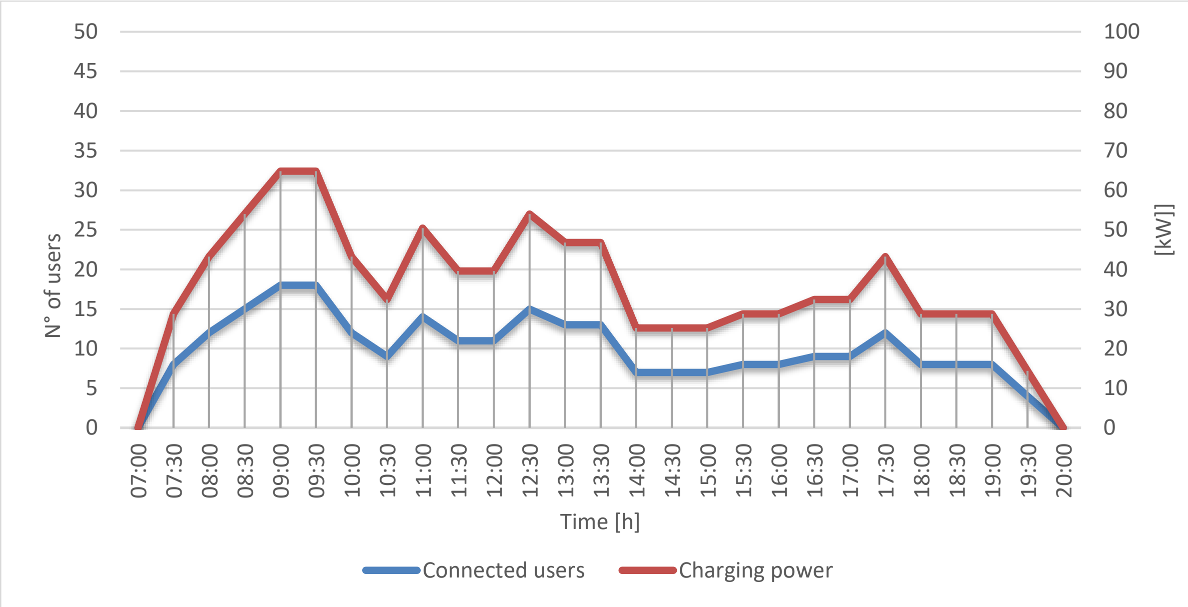
In Table 6-10 it is shown the scheduling of the charging for the 50 users during the day. The distribution is done automatically by the App and it aims to avoid peaks of charging load where many users are connected at the same time, while also fulfilling the energy needs for all.



Graph 6-6 Distributon of the connected users and the charging load during the day – Controlled charging

In this case, the charging load is distributed more equally during the day, as shown in Graph 6-6. The peak charging power is 64.8 kW, during 09^{00}-09^{30} where 18 users are connected, which is less than half of the peak power in the uncontrolled charging scenario. The average charging power is 35.2 kW.

Installing some photovoltaic modules in the available roof spaces could also help the integration of more EVs/PHEVs in the university, as more charging columns could be installed. Since the vehicles are charged only during the day, this would bring many advantages:

- Grid stability is not compromised as (almost) all the charging power could be provided from the PV system
- Less (or free) charging cost
- More users are attracted to switch or buy an EV/PHEV
- Clean and inexhaustible energy for the charging to also help the environment

Based on the charging power demand from this scenario, a 50-70 kWp PV system could be installed to satisfy the 50 users' charging needs.

6.6 Conclusions

As shown in Figure 6-2, from the survey it emerged that :

- 60% of the users who completed the survey had a positive result on the convenience of switching to an electric/hybrid car
- the remaining 40% could not recover the initial cost expense within 10 years on the basis of their annual routes, even though there was an effective annual saving on fuel costs and CO2 emissions reduction

This means that in absence of subsidies by the government or other discounts, the initial cost of electric/hybrid car is still an obstacle for the total green transition.

The users who could appreciate an economical convenience, besides helping the environment, were more likely to choose a hybrid car, instead of a plug-in hybrid or pure electrical, mostly because of the higher cost of the last two types which allocate a bigger battery pack.

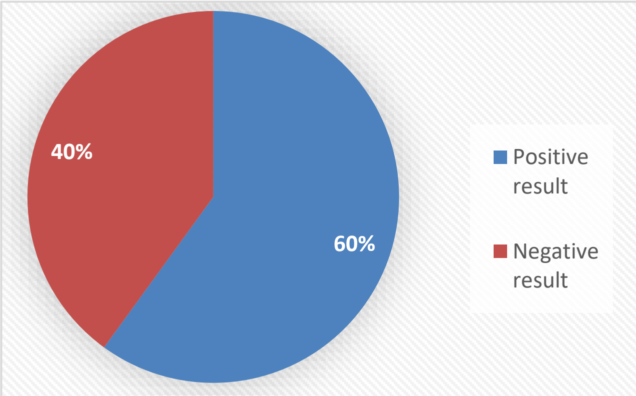


Figure 6-2 Distribution of the users convenience in switching to an electric/hybrid car (Source: Survey on staff mobility)

Hybrid cars instead, have a much smaller battery, their cost is slightly higher than a conventional ICE car and also have less fuel consumption, which makes users more attracted to buy them.

21% of the users willing to switch from their actual ICE car, chose an electric/plug-in hybrid car, which can take advantage of the charging stations inside the university.

Since switching to an EV/PHEV might condition somehow the user's daily scheduling of the charging in case of a controlled charging (booking the charging spot with an App, not always available at the desired hour), a high number o charging spots should be taken into consideration to be installed, to avoid congestion and make the charging available to all during the day.
An optimistic scenario could be installing 20 charging columns, which can support 2 vehicles at the time with slow charging (2.2 – 3.6 kW).
In order to not compromise the grid stability and reduce charging power peaks, a controlled charging should be implemented, while also giving the possibility to all users to charge their EV/PHEV.

The EV/PHEV integration could be more feasible by installing a PV system, which can support the grid when charging. This way the grid operation would be more stable, as more vehicles could charge at the same time without compromising grid stability and the charging cost would reduce significantly.

7 Conclusions

In the near future, electricity consumption and generation is going to change significantly in Denmark. From the generation point of view, there will be an increase of renewable energy, mainly from wind power. On the other side, electricity consumers will request new services such as being able to plug their electrical vehicles at home regularly.

This thesis aims to see how the aggregation of the EVs affects the grid in a neighbourhood, and to develop a smart charging plan. By doing this, the limits of the distribution grid will be guaranteed.

Since the action plan of the Danish government, whose purpose is to reduce the greenhouse gasses emission, the number of EVs on roads has been increased. So, in order to analyze the grid and see its performance, a study about driving profiles has been done in Chapter 3, where some statistics are presented about arrival times and distances travelled during the day. On the basis of this, it has been generated some random data in order to make the simulations more realistic. After the interpretation of this data, there have been simulated two different cases of charging modes. One regards the dumb charging and the other the smart charging.

In Chapter 4, it has been carried out an initial simulation to observe the operation of the grid without the aggregation of EVs and then its behavior when applying dumb charging. In this case, it has been studied how many vehicles can the grid support during the peak hour (from 17 to 18) in four different scenarios. As it has been described, it is during a winter weekday when the grid reaches its maximum capacity. This is the worst case considering that the grid can only support 24 EVs of a charging power of 11 kW.
This is because of extra consumption such as lighting and heating. It has also been observed that Feeder 4 is the weakest feeder, which is not able to support many EVs. It was observed that the main limiting factor is the voltage magnitude of the busbars $(V \geq 0.94\, p.u)$, while the transformer rating and line loading $(\leq 100\%)$ were never exceeded.

After having detected, as expected, that by implementing dumb charging the grid is not able to deliver the necessary power to all vehicles, the smart charging has been implemented. An optimal charging plan was made, where the vehicles were distributed among the different charging hours, prioritizing the ones with lowest electricity price. The results show that by applying this control, the supply of electricity matches the demand. Also, from the customer's economical point of view it is worth to follow this plan since the price of the charging can be reduced up to 22630 DKK.

In the Politecnico case, the green mobility transition is still economically not profitable for all users. This is mostly because of the higher cost of the electric/hybrid cars and the lack of subsidies from the government. Users could appreciate an annual saving when switching from their actual ICE car, but only 60% of them had a long-term profit, mostly when switching to a hybrid car.

To make the EV/PHEV transition more attractive and practical, some charging spots inside the university could be installed. With a controlled charging and a possible PV system installation, a considerable number of columns could be installed without compromising grid stability, but also making the charging available to more users, greener and less expensive.

Future Work

During the research of the current thesis, some other applicable topics were identified and could be considered for future studies.

Taking into consideration the increasing number of the EVs in the future, the reorganization of the grid structure in order to have shorter feeders should be considered, in order to reduce the voltage issues and improve the behavior of the grid (Feeder 4 could be divided into 2 independent feeders). Simulating the implementation of distributed generation could also be a solution for the voltage problems in the long feeders.

The power quality of the distribution grid should be investigated. Hence, with the purpose to improve the behavior of the grid, the harmonics and flicker issues should be analyzed.

The information and communication technology has considerably increased and developed lately, therefore the smart grid concept needs to be further studied.

At the Politecnico, the grid capability to charge a high number of EVs needs to be tested, along with the availability of space to install many charging spots. Further studies of a PV system to support the charging are necessary, along with the grid restructuration to support V2G for the users, to make the green mobility transition more attractive and feasible for the users.

The possibility of regulating the energy market by integrating the V2G concept should be discussed and simulated along with the smart charging, thus an economical benefit might also be achieved by the EVs owners. Also, more research should be done on the EV battery's characteristics in order to serve as energy storages.

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Appendix

Households consumption, based on transformer loading %

Hour	Season			
	Winter weekday	Summer weekday	Summer weekend	Winter weekend
0	4,544763	5,139661	5,824286	4,245756
1	3,913497	4,587759	5,502031	3,984767
2	3,364628	3,860249	4,735175	4,539452
3	3,024611	3,751226	3,005712	4,020695
4	2,901335	3,716913	2,440736	4,594266
5	2,791818	3,80954	2,528453	4,124156
6	3,150456	3,798813	3,016715	3,764504
7	6,124565	5,910307	3,819497	3,113568
8	9,432779	7,312786	4,113688	2,547877
9	11,698417	8,464643	7,228529	6,127042
10	8,946367	8,824989	7,848346	5,829095
11	9,604442	9,598843	8,586813	4,904361
12	12,188337	9,599368	9,653749	5,733092
13	9,026578	9,617554	10,77611	9,051873
14	12,381916	9,219547	9,862385	8,463742
15	8,530184	8,645659	10,811298	9,377278
16	11,969647	9,330101	11,516624	6,779228
17	13,381927	10,54942	12,121353	13,277171
18	15,841096	12,968498	11,733103	9,930057
19	13,449233	11,069751	11,822206	8,868762
20	12,415897	8,187116	11,195592	8,639357
21	11,910115	7,931042	8,970741	11,206474
22	9,792086	7,686453	7,367097	6,946448
23	7,744976	6,237846	6,23365	8,232977

Generation of distances travelled for each vehicle

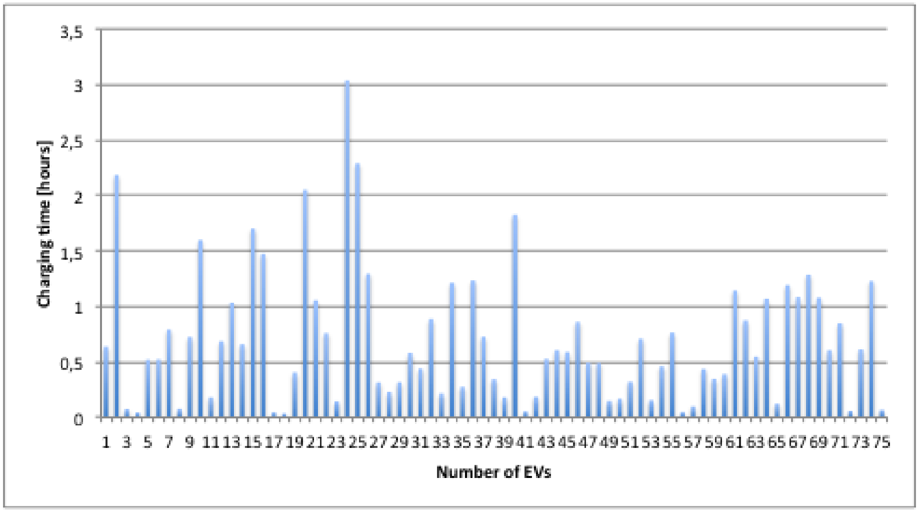
```
clc;
clear all;
d = random('Weibull',40,1,75,1);
hist(d,75)
```

EV driving distance travelled

Number of Evs	Distance [km]	Number of Evs	Distance [km]
EV1	34,96	**EV39**	9,93
EV2	120,11	**EV40**	100,47
EV3	4,09	**EV41**	2,93
EV4	2,27	**EV42**	10,16
EV5	28,46	**EV43**	28,80
EV6	28,60	**EV44**	33,22
EV7	43,42	**EV45**	32,23
EV8	4,21	**EV46**	47,32
EV9	39,85	**EV47**	27,05
EV10	87,86	**EV48**	26,87
EV11	9,93	**EV49**	8,05
EV12	37,69	**EV50**	9,19
EV13	56,80	**EV51**	17,58
EV14	36,26	**EV52**	38,85
EV15	93,55	**EV53**	8,35
EV16	81,01	**EV54**	25,18
EV17	2,39	**EV55**	41,91
EV18	1,79	**EV56**	2,52
EV19	22,12	**EV57**	5,30
EV20	112,68	**EV58**	23,90
EV21	57,96	**EV59**	18,96
EV22	41,63	**EV60**	21,31
EV23	7,88	**EV61**	62,86
EV24	166,93	**EV62**	47,99
EV25	125,84	**EV63**	30,12
EV26	71,12	**EV64**	58,70
EV27	17,29	**EV65**	6,77
EV28	12,49	**EV66**	65,44
EV29	17,37	**EV67**	59,50
EV30	31,86	**EV68**	70,71
EV31	24,13	**EV69**	59,20
EV32	48,65	**EV70**	33,23
EV33	11,79	**EV71**	46,71

EV34	66,65	**EV72**	3,19
EV35	15,03	**EV73**	33,74
EV36	67,82	**EV74**	49,36
EV37	39,93	**EV75**	4,00
EV38	18,76		

Charging time for smart charging simulation (charging power of 11kW)



Generation of arrival time's data

```
x=[8:0.5:24];
norm=normpdf(x,17,1.5);
pd=makedist('Normal', 'mu', 17, 'sigma', 1.5)
A=random (pd,1,75)
% y = round(A,0)
data=ceil(A)
plot(x,norm)
```

List of arrival times generated

EV nr.	Rounded time of arrival [hours]	Number of EV	Rounded time of arrival [hours]
EV1	13	**EV39**	18
EV2	14	**EV40**	18
EV3	15	**EV41**	18
EV4	15	**EV42**	18
EV5	15	**EV43**	18
EV6	15	**EV44**	18
EV7	16	**EV45**	18
EV8	16	**EV46**	18
EV9	16	**EV47**	18
EV10	16	**EV48**	18
EV11	16	**EV49**	18
EV12	16	**EV50**	19
EV13	16	**EV51**	19
EV14	16	**EV52**	19
EV15	16	**EV53**	19
EV16	16	**EV54**	19
EV17	16	**EV55**	19
EV18	16	**EV56**	19
EV19	16	**EV57**	19
EV20	16	**EV58**	19
EV21	16	**EV59**	19
EV22	17	**EV60**	19
EV23	17	**EV61**	19
EV24	17	**EV62**	19
EV25	17	**EV63**	20
EV26	17	**EV64**	20
EV27	17	**EV65**	20
EV28	17	**EV66**	20
EV29	17	**EV67**	20
EV30	17	**EV68**	20
EV31	17	**EV69**	20
EV32	17	**EV70**	20
EV33	17	**EV71**	20
EV34	17	**EV72**	21
EV35	17	**EV73**	22
EV36	18	**EV74**	22
EV37	18	**EV75**	23
EV38	18		

Elspot table of electricity prices with tax

Hours	Windy day [DKK/MWh]	No windy day [DKK/MWh]
1	121,83	196,39
2	118,47	192,66
3	116,53	194,30
4	117,65	186,99
5	118,55	194,23
6	123,70	200,05
7	128,70	246,01
8	132,73	413,02
9	134,74	457,79
10	133,70	438,02
11	132,58	442,05
12	131,08	420,93
13	129,14	439,28
14	126,76	431,67
15	125,19	412,05
16	122,88	393,17
17	124,07	539,35
18	126,91	694,12
19	126,01	592,19
20	122,43	524,58
21	116,91	375,86
22	115,41	300,94
23	110,94	252,13
24	78,78	223,10

Matlab script for allocating each vehicle at the hour of lowest price

```
clc
clear all
load Arrival_times
load Hour_price
load Energy_each_vehicle
EV=1:75;
a=[0 Hour_price(1,:)];%HOURS
Table_result = zeros(length(EV)+1,length(Hour_price(1,:))+1,1);
```

```
Table_result(1,:,1) = a;
for i=1:length (Energy_each_vehicle)
     for ev=1:length(EV)
         Table_result(ev+1,1,1) = EV(ev);
        for hp= 1:length(a)
           if Arrival_Times(i)<a(hp)
                Ey(i)=Ey(i)+Energy_each_vehicle(i);
                Table_result(i+1,hp,1) = Energy_each_vehicle (i) ;
                break
            else if Arrival_Times(i) == 22
                Table_result(i+1,hp+2,1) = Energy_each_vehicle (i)
                break
            else if Arrival_Times(i) == 23
                Table_result(i+1,hp+3,1) = Energy_each_vehicle (i)
                break
                end
                end
           end
        end
     end
end
```

If E > 11kWh allocate the vehicle in next hours

```
clc
run Hours_vehicles
i=0;
j=0;
for i=2:75;
        if Table_result(i,2)>11
           Table_result(i,3)= ( Table_result(i,2)-11);
           Table_result(i,2)=11;

          if Table_result(i,3)>11
              Table_result(i,4)=Table_result(i,3)-11;
               Table_result(i,3)=11;


              if Table_result(i,4)>11
                 Table_result(i,5)=Table_result(i,4)-11;
                 Table_result(i,4)=11;
              end
       end
        end
end
```

Load flow calculation from the smart charging scenario

Load Flow Calculation	Edge Elements

AC Load Flow, balanced, positive sequence		Automatic Model Adaptation for Convergence	No
Automatic Tap Adjust of Transformers	No	Max. Acceptable Load Flow Error for	
Consider Reactive Power Limits	No	Nodes	1,00 kVA
		Model Equations	0,10 %

DIgSILENT	Project:		
PowerFactory			
15.2.1	Date: 5/25/2016		

Grid: 75 House Grid	System Stage: 75 House Grid	Study Case: WPS2-830 Semester Project	Annex: / 1

Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power-factor [-]	Current [kA]	Current [p.u.]
F1-EV01	Lod		B1	10,206	0,000	1,00	0,015	0,963
F1-EV02	Lod		B2	9,993	0,000	1,00	0,015	0,953
F1-EV03	Lod		B2	9,993	0,000	1,00	0,015	0,953
F1-EV04	Lod		B3	9,791	0,000	1,00	0,015	0,943
F1-EV05	Lod		B3	9,791	0,000	1,00	0,015	0,943
F1-EV06	Lod		B4	9,909	0,000	1,00	0,015	0,949
F1-EV07	Lod		B4	0,000	-0,000	1,00	0,000	0,000
F1-EV08	Lod		B5	0,000	-0,000	1,00	0,000	0,000
F1-EV09	Lod		B5	0,000	-0,000	1,00	0,000	0,000
F1-EV10	Lod		B5	0,000	-0,000	1,00	0,000	0,000
F1-EV11	Lod		B5	0,000	-0,000	1,00	0,000	0,000
F1-EV12	Lod		B6	0,000	-0,000	1,00	0,000	0,000
F1-EV13	Lod		B6	0,000	-0,000	1,00	0,000	0,000
F1-EV14	Lod		B6	0,000	-0,000	1,00	0,000	0,000
F1-EV15	Lod		B6	0,000	-0,000	1,00	0,000	0,000
F1-H1-M	Lod		B1	0,143	0,035	0,97	0,000	0,977
F1-H10-H	Lod		B5	0,630	0,156	0,97	0,001	0,965
F1-H11-L	Lod		B5	0,078	0,019	0,97	0,000	0,965
F1-H12-H	Lod		B6	0,636	0,158	0,97	0,001	0,968
F1-H13-M	Lod		B6	0,139	0,035	0,97	0,000	0,968
F1-H14-M	Lod		B6	0,139	0,035	0,97	0,000	0,968
F1-H15-M	Lod		B6	0,139	0,035	0,97	0,000	0,968
F1-H2-M	Lod		B2	0,140	0,035	0,97	0,000	0,971
F1-H3-M	Lod		B2	0,140	0,035	0,97	0,000	0,971
F1-H4-H	Lod		B3	0,630	0,156	0,97	0,001	0,965

F1-H5-M	Lod		B3	0,138	0,034	0,97	0,000	0,965
F1-H6-L	Lod		B4	0,079	0,020	0,97	0,000	0,969
F1-H7-M	Lod		B4	0,139	0,035	0,97	0,000	0,969
F1-H8-M	Lod		B5	0,138	0,034	0,97	0,000	0,965
F1-H9-M	Lod		B5	0,138	0,034	0,97	0,000	0,965
F2-EV01	Lod		B7	10,451	0,000	1,00	0,015	0,975

| Grid: 75 House Grid System Stage: 75 House Grid | Study Case: WPS2-830 Semester Project | Annex: / 2 |

Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power.- factor [-]	Current [kA]	[p.u.]
F2-EV02	Lod		B7	10,451	0,000	1,00	0,015	0,975
F2-EV03	Lod		B8	10,132	0,000	1,00	0,015	0,960
F2-EV04	Lod		B8	10,132	0,000	1,00	0,015	0,960
F2-EV05	Lod		B9	9,904	0,000	1,00	0,015	0,949
F2-EV06	Lod		B9	9,904	0,000	1,00	0,015	0,949
F2-EV07	Lod		B9	9,904	0,000	1,00	0,015	0,949
F2-EV08	Lod		B10	9,951	-0,000	1,00	0,015	0,951
F2-EV09	Lod		B10	9,951	-0,000	1,00	0,015	0,951
F2-EV10	Lod		B11	9,822	0,000	1,00	0,015	0,945
F2-EV11	Lod		B11	9,822	0,000	1,00	0,015	0,945
F2-EV12	Lod		B12	9,807	0,000	1,00	0,015	0,944
F2-EV13	Lod		B12	9,807	0,000	1,00	0,015	0,944
F2-EV14	Lod		B12	9,807	0,000	1,00	0,015	0,944
F2-EV15	Lod		B13	0,000	-0,000	1,00	0,000	0,000
F2-EV16	Lod		B13	0,000	-0,000	1,00	0,000	0,000
F2-EV17	Lod		B14	0,000	-0,000	1,00	0,000	0,000
F2-EV18	Lod		B14	0,000	-0,000	1,00	0,000	0,000
F2-EV19	Lod		B14	0,000	-0,000	1,00	0,000	0,000
F2-EV20	Lod		B15	0,000	-0,000	1,00	0,000	0,000
F2-EV21	Lod		B15	0,000	-0,000	1,00	0,000	0,000
F2-EV22	Lod		B15	0,000	-0,000	1,00	0,000	0,000
F2-H16-M	Lod		B7	0,145	0,036	0,97	0,000	0,984
F2-H17-M	Lod		B7	0,145	0,036	0,97	0,000	0,984
F2-H18-M	Lod		B8	0,142	0,035	0,97	0,000	0,975
F2-H19-M	Lod		B8	0,142	0,035	0,97	0,000	0,975
F2-H20-M	Lod		B9	0,139	0,035	0,97	0,000	0,968
F2-H21-M	Lod		B9	0,139	0,035	0,97	0,000	0,968
F2-H22-H	Lod		B9	0,636	0,158	0,97	0,001	0,968
F2-H23-H	Lod		B10	0,639	0,158	0,97	0,001	0,970
F2-H24-H	Lod		B10	0,639	0,158	0,97	0,001	0,970
F2-H25-M	Lod		B11	0,138	0,034	0,97	0,000	0,966
F2-H26-M	Lod		B11	0,138	0,034	0,97	0,000	0,966
F2-H27-M	Lod		B12	0,138	0,034	0,97	0,000	0,965

F2-H28-L	Lod		B12	0,078	0,019	0,97	0,000	0,965
F2-H29-M	Lod		B12	0,138	0,034	0,97	0,000	0,965
F2-H30-M	Lod		B13	0,138	0,034	0,97	0,000	0,965
F2-H31-H	Lod		B13	0,631	0,156	0,97	0,001	0,965
F2-H32-L	Lod		B14	0,078	0,019	0,97	0,000	0,965
F2-H33-M	Lod		B14	0,138	0,034	0,97	0,000	0,965
F2-H34-H	Lod		B14	0,631	0,156	0,97	0,001	0,965
F2-H35-M	Lod		B15	0,138	0,034	0,97	0,000	0,965
F2-H36-M	Lod		B15	0,138	0,034	0,97	0,000	0,965
F2-H37-L	Lod		B15	0,078	0,019	0,97	0,000	0,965
F2-H54-M	Lod		B22	0,138	0,034	0,97	0,000	0,964

| Grid: 75 House Grid | System Stage: 75 House Grid | Study Case: WPS2-830 Semester Project | Annex: / 3 |

Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power.- factor [-]	Current [kA]	[p.u.]
F2-H55-M	Lod		B22	0,138	0,034	0,97	0,000	0,964
F2-H56-L	Lod		B22	0,078	0,019	0,97	0,000	0,964
F3-EV01	Lod		B16	0,000	-0,000	1,00	0,000	0,000
F3-H38-M	Lod		B16	0,149	0,037	0,97	0,000	0,994
F4-EV01	Lod		B17	10,018	-0,000	1,00	0,015	0,954
F4-EV02	Lod		B17	10,018	-0,000	1,00	0,015	0,954
F4-EV03	Lod		B17	10,018	-0,000	1,00	0,015	0,954
F4-EV04	Lod		B17	10,018	-0,000	1,00	0,015	0,954
F4-EV05	Lod		B18	9,747	0,000	1,00	0,015	0,941
F4-EV06	Lod		B18	9,747	0,000	1,00	0,015	0,941
F4-EV07	Lod		B18	9,747	0,000	1,00	0,015	0,941
F4-EV08	Lod		B19	9,918	0,000	1,00	0,015	0,950
F4-EV09	Lod		B19	9,918	0,000	1,00	0,015	0,950
F4-EV10	Lod		B19	9,918	0,000	1,00	0,015	0,950
F4-EV11	Lod		B20	0,000	-0,000	1,00	0,000	0,000
F4-EV12	Lod		B20	0,000	-0,000	1,00	0,000	0,000
F4-EV13	Lod		B20	0,000	-0,000	1,00	0,000	0,000
F4-EV14	Lod		B21	0,000	-0,000	1,00	0,000	0,000
F4-EV15	Lod		B21	0,000	-0,000	1,00	0,000	0,000
F4-EV16	Lod		B22	0,000	-0,000	1,00	0,000	0,000
F4-EV17	Lod		B22	0,000	-0,000	1,00	0,000	0,000
F4-EV18	Lod		B22	0,000	-0,000	1,00	0,000	0,000
F4-EV19	Lod		B23	0,000	-0,000	1,00	0,000	0,000
F4-EV20	Lod		B23	0,000	-0,000	1,00	0,000	0,000
F4-EV21	Lod		B23	0,000	-0,000	1,00	0,000	0,000
F4-EV22	Lod		B24	0,000	-0,000	1,00	0,000	0,000
F4-EV23	Lod		B24	0,000	-0,000	1,00	0,000	0,000
F4-EV24	Lod		B25	0,000	-0,000	1,00	0,000	0,000

F4-EV25	Lod		B25	0,000	-0,000	1,00	0,000	0,000
F4-EV26	Lod		B25	0,000	-0,000	1,00	0,000	0,000
F4-EV27	Lod		B25	0,000	-0,000	1,00	0,000	0,000
F4-EV28	Lod		B25	0,000	-0,000	1,00	0,000	0,000
F4-EV29	Lod		B26	0,000	-0,000	1,00	0,000	0,000
F4-EV30	Lod		B26	0,000	-0,000	1,00	0,000	0,000
F4-EV31	Lod		B27	0,000	-0,000	1,00	0,000	0,000
F4-EV32	Lod		B27	0,000	-0,000	1,00	0,000	0,000
F4-EV33	Lod		B27	0,000	-0,000	1,00	0,000	0,000
F4-EV34	Lod		B27	0,000	-0,000	1,00	0,000	0,000
F4-H39-M	Lod		B17	0,140	0,035	0,97	0,000	0,972
F4-H40-M	Lod		B17	0,140	0,035	0,97	0,000	0,972
F4-H41-M	Lod		B17	0,140	0,035	0,97	0,000	0,972
F4-H42-M	Lod		B17	0,140	0,035	0,97	0,000	0,972
F4-H43-M	Lod		B18	0,137	0,034	0,97	0,000	0,964
F4-H44-M	Lod		B18	0,137	0,034	0,97	0,000	0,964

| Grid: 75 House Grid System Stage: 75 House Grid | Study Case: WPS2-830 Semester Project | Annex: / 4 |

Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power.- factor [-]	Current [kA]	[p.u.]
F4-H45-H	Lod		B18	0,628	0,156	0,97	0,001	0,964
F4-H46-M	Lod		B19	0,139	0,035	0,97	0,000	0,969
F4-H47-M	Lod		B19	0,139	0,035	0,97	0,000	0,969
F4-H48-L	Lod		B19	0,079	0,020	0,97	0,000	0,969
F4-H49-M	Lod		B20	0,139	0,035	0,97	0,000	0,968
F4-H50-M	Lod		B20	0,139	0,035	0,97	0,000	0,968
F4-H51-M	Lod		B20	0,139	0,035	0,97	0,000	0,968
F4-H52-M	Lod		B21	0,138	0,034	0,97	0,000	0,965
F4-H53-M	Lod		B21	0,138	0,034	0,97	0,000	0,965
F4-H57-M	Lod		B23	0,138	0,034	0,97	0,000	0,964
F4-H58-M	Lod		B23	0,138	0,034	0,97	0,000	0,964
F4-H59-M	Lod		B23	0,138	0,034	0,97	0,000	0,964
F4-H60-M	Lod		B24	0,138	0,034	0,97	0,000	0,964
F4-H61-M	Lod		B24	0,138	0,034	0,97	0,000	0,964
F4-H62-M	Lod		B25	0,138	0,034	0,97	0,000	0,964
F4-H63-M	Lod		B25	0,138	0,034	0,97	0,000	0,964
F4-H64-M	Lod		B25	0,138	0,034	0,97	0,000	0,964
F4-H65-M	Lod		B25	0,138	0,034	0,97	0,000	0,964
F4-H66-L	Lod		B25	0,078	0,019	0,97	0,000	0,964
F4-H67-M	Lod		B26	0,138	0,034	0,97	0,000	0,964
F4-H68-M	Lod		B26	0,138	0,034	0,97	0,000	0,964
F4-H69-M	Lod		B27	0,137	0,034	0,97	0,000	0,964
F4-H70-M	Lod		B27	0,137	0,034	0,97	0,000	0,964

F4-H71-M	Lod		B27	0,137	0,034	0,97	0,000	0,964
F4-H72-H	Lod		B27	0,628	0,156	0,97	0,001	0,964
F5-EV01	Lod		B28	0,000	-0,000	1,00	0,000	0,000
F5-EV02	Lod		B28	0,000	-0,000	1,00	0,000	0,000
F5-EV03	Lod		B28	0,000	-0,000	1,00	0,000	0,000
F5-H73-H	Lod		B28	0,680	0,170	0,97	0,001	0,994
F5-H74-M	Lod		B28	0,149	0,037	0,97	0,000	0,994
F5-H75-M	Lod		B28	0,149	0,037	0,97	0,000	0,994
External Grid	Xnet		LV 10 kV terminal	330,465	18,174	1,00	0,019	0,000
L1	Lne	45,63	LV 0.4 kV terminal	65,702	1,422	1,00	0,096	0,456
			B1	-63,943	-1,009	-1,00	0,096	0,456
L10	Lne	41,14	B8	73,847	1,247	1,00	0,111	0,411
			B10	-73,187	-1,017	-1,00	0,111	0,411
L11	Lne	21,73	B10	20,045	0,081	1,00	0,030	0,217
			B11	-19,915	-0,065	-1,00	0,030	0,217
L12	Lne	23,11	B12	-31,736	-0,569	-1,00	0,049	0,231
			B10	31,967	0,624	1,00	0,049	0,231
L13	Lne	1,48	B13	-1,969	-0,487	-0,97	0,003	0,015
			B12	1,970	0,488	0,97	0,003	0,015
L14	Lne	0,95	B13	0,847	0,209	0,97	0,001	0,010
			B14	-0,846	-0,209	-0,97	0,001	0,010

| Grid: 75 House Grid System Stage: 75 House Grid | Study Case: WPS2-830 Semester Project | Annex: / 5 |

Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power-factor [-]	Current [kA]	[p.u.]
L15	Lne	0,40	B13	0,354	0,088	0,97	0,001	0,004
			B15	-0,354	-0,088	-0,97	0,001	0,004
L16	Lne	0,16	LV 0.4 kV terminal	0,149	0,037	0,97	0,000	0,002
			B16	-0,149	-0,037	-0,97	0,000	0,002
L17	Lne	58,91	B17	-105,150	-1,459	-1,00	0,159	0,589
			LV 0.4 kV terminal	109,040	2,813	1,00	0,159	0,589
L18	Lne	33,01	B17	30,549	0,269	1,00	0,046	0,330
			B18	-30,134	-0,218	-1,00	0,046	0,330
L19	Lne	19,04	B17	33,976	1,058	1,00	0,051	0,190
			B19	-33,808	-0,999	-1,00	0,051	0,190
L2	Lne	38,25	B1	53,596	0,975	1,00	0,080	0,382
			B2	-53,037	-0,843	-1,00	0,080	0,382
L20	Lne	2,15	B19	3,704	0,917	0,97	0,006	0,021
			B20	-3,702	-0,916	-0,97	0,006	0,021
L21	Lne	2,45	B20	3,285	0,812	0,97	0,005	0,025
			B21	-3,263	-0,807	-0,97	0,005	0,025
L22	Lne	0,40	B22	-0,353	-0,087	-0,97	0,001	0,004
			B21	0,353	0,087	0,97	0,001	0,004

L23	Lne	0,47	B23	-0,413	-0,102	-0,97	0,001	0,005
			B21	0,413	0,102	0,97	0,001	0,005
L24	Lne	1,67	B24	-2,220	-0,549	-0,97	0,004	0,017
			B21	2,221	0,549	0,97	0,004	0,017
L25	Lne	0,71	B24	0,628	0,155	0,97	0,001	0,007
			B25	-0,628	-0,155	-0,97	0,001	0,007
L26	Lne	1,48	B26	-1,316	-0,326	-0,97	0,002	0,015
			B24	1,317	0,326	0,97	0,002	0,015
L27	Lne	1,17	B27	-1,040	-0,257	-0,97	0,002	0,012
			B26	1,041	0,257	0,97	0,002	0,012
L28	Lne	1,05	B28	-0,978	-0,245	-0,97	0,001	0,011
			LV 0.4 kV terminal	0,979	0,245	0,97	0,001	0,011
L3	Lne	23,31	B2	21,547	0,457	1,00	0,033	0,233
			B3	-21,328	-0,431	-1,00	0,033	0,233
L4	Lne	12,15	B2	11,226	0,319	1,00	0,017	0,121
			B4	-11,179	-0,314	-1,00	0,017	0,121
L5	Lne	1,11	B3	0,984	0,243	0,97	0,002	0,011
			B5	-0,983	-0,243	-0,97	0,002	0,011
L6	Lne	1,18	B4	1,054	0,261	0,97	0,002	0,012
			B6	-1,053	-0,261	-0,97	0,002	0,012
L7	Lne	81,45	LV 0.4 kV terminal	150,789	3,124	1,00	0,220	0,815
			B7	-148,500	-2,327	-1,00	0,220	0,815
L8	Lne	69,83	B7	127,309	2,257	1,00	0,189	0,698
			B8	-125,361	-1,579	-1,00	0,189	0,698
L9	Lne	33,27	B8	30,969	0,265	1,00	0,047	0,333
			B9	-30,618	-0,222	-1,00	0,047	0,333

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Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power.- factor [-]	Current [kA]	[p.u.]
Transfomer	Tr2	82,74	LV 10 kV terminal	330,465	18,174	1,00	0,019	0,827
			LV 0.4 kV terminal	-326,658	-7,641	-1,00	0,476	0,825