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TESI DI LAUREA MAGISTRALE

Flexibility procurement by EVs in a Danish active distribution network: Study cases from the island of Bornholm

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Udbud af fleksibilitet fra elbiler i et aktivt dansk distributionsnet: Et studie fra Bornholm

Approvvigionamento di flessibilità tramite veicoli elettrici in una rete di distribuzione attiva danese: Studi relativi all'isola di Bornholm

Master's Thesis, by Lisa Calearo

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PREFACE

This MSc thesis is prepared at the Department of Electrical Engineering of the Technical University of Denmark in fulfilment of the requirements for acquiring both a Master of Science in Sustainable Energy at the Technical University of Denmark (DTU) and a Master of Science in Electrical Energy Engineering at the University of Padua, in accordance with the double degree program T.I.M.E. (Top Industrial Managers for Europe).

The thesis aims to give a contribution to the Danish Research Project "ACES - Across Continents Electric Vehicle Services".

Under the supervision of Mattia Marinelli, Roberto Turri, Andreas Thingvad and Hans Henrik Ipsen, this work has been carried out between January and June 2018 at the Department of Electrical Engineering (DTU Elektro), at the Technical University of Denmark (DTU). The thesis was set to count 30 ECTS for the Master of Science in Sustainable Energy and 21 ECTS for the Master of Science in Electrical Energy Engineering.

Virum, June 18, 2018

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Finally, I want to thank my family for always being with me both in the happy and the hard periods. You have made me the person I am today, and this experience would not be possible without you.

Abstract

Nowadays the need for reducing the carbon pollution and oil dependency, mainly due to the climate change, is strongly increasing.
As part of the ongoing project "Across Continents Electric Vehicle Services (ACES)" [1], this thesis analyses the impact of two LV grids of the island of Bornholm with the penetration of the electric vehicles (EVs). The targets of the Danish government for the 2050 is of 100% energy production by RES. Today the Danish national level is 31% [2], therefore the goal of producing 50% of the energy by RES in 2030 is far way from what fulfilled until now. The actual value of 31% comes from imported biofuels, opening an opportunity window to the transport electrification as a sustainable way to achieve high level of renewable energy. For this reason the industry trends and the clean-air regulations are becoming more strict for the car manufacturers, making the major producers to shift their market toward a greener direction. This is usually resulting in a price drop of the most expensive component, the battery, that would lead the consumers to approve the market shift into a electrified transportation sector.

The charging peak is assumed to coincide with the domestic consumption peak, therefore an high EV penetration amounts to a big change for the electricity system. The network has to deal with a load increase that is difficult to predict, since it would depend on the EV penetration level, and on the human behaviour.

In the past the distribution system operators (DSOs), mainly responsible for the management of the network, dealt with reliability problems by reinforcing the grid. Now the DERs - distributed energy resources - are widespread and the reinforcement is not always, technically and/or economically, efficient anymore. The unique solution seems to be a more real-time approach that benefits from the same resources procuring flexibility. The EVs, as part of the DERs, instead of being the problem are considered the tool to provide flexibility services.

In this thesis two feeders in the Bornholm grid are analysed. They are located in opposite areas of the island and subjected to different loading and customers' characteristics: the investigation assesses the value of the grid service of the EVs in the distribution network, highlighting differences and similarities between the feeders. Starting from the existing grid topologies and customer loadings, several EV penetration scenarios, based on realistic driving and charging patterns, are tested by means of temporal load flows. Furthermore, the EVs are used as a flexible provision for the power system and its market, in order to maximize the benefits of the system, aggregator and user. This thesis is based on real data (some directly measured and others elaborated) aiming to create a realistic and feasible scenario as a small scale pilot project for future studies.

SOMMARIO

Oggigiorno, principalmente a causa dei cambiamenti climatici, la necessità di ridurre le emissioni di carbonio e la dipendenza dal petrolio è in forte aumento.
In quanto parte del progetto in corso "Across Continents Electric Vehicle Services (ACES)" [1], questa tesi analizza l'impatto dei veicoli elettrici (VE) in due reti di distribuzione presenti nell'isola di Bornholm. L'obiettivo del governo danese per il 2050 è di produrre energia utilizzando il 100% energie rinnovabili. Oggi il livello nazionale danese è al 31% [2], perciò l'obiettivo di produrre 50% di energia da fonti energetiche rinnovabili nel 2030 è ancora lontano da raggiungere. Il 31% deriva dall'importazione dei biocarburanti, dando spazio al settore dei trasporti come modo sostenibile per raggiungere un alto livello di energia rinnovabile.
Conseguentemente le tendenze e le normative nel settore dei trasporti stanno diventando sempre più stringenti per le case automobilistiche, per far sì che i principali produttori spostino il loro mercato verso una direzione più ecologica, come i veicoli elettrici. Questo si traduce in un calo dei prezzi del componente più costoso, la batteria, portando l'approvazione da parte dei consumatori al trasferimento del mercato nel settore di trasporto elettrificato.

Considerando le quotidiane abitudini della civiltà, si presume che la carica dei VE possa andare a coincidere con il picco del consumo elettrico giornaliero; pertanto un'elevata penetrazione dei VE potrebbe portare ad un grande cambiamento per il sistema elettrico. La rete si troverebbe ad affrontare un aumento del carico pressochè imprevedibile, in quanto dipendente dal livello di penetrazione dei VE e dal comportamento umano.

Fino ad ora i gestori dei sistemi di distribuzione hanno affrontato problemi di affidabilità rafforzando i vari componenti della rete. Oggi, a causa della distribuzione di varie risorse energetiche nella rete, il rinforzo della rete non è sempre, tecnicamente e/o economicamente, efficiente. La soluzione più appropriata sembra essere un approccio in tempo reale, che riesca a trarre beneficio dalle stesse risorse che procurano flessibilità. Essendo parte delle risorse distribuite nella rete, i VE invece di esser considerati il problema, possono diventare lo strumento per fornire flessibilità al sistema elettrico.

In questa tesi vengono analizzate due reti di bassa tensione, Tejn e Rønne, localizzate in aree opposte dell'isola di Bornholm. Nonostante le diverse caratteristiche di carico, le due reti rappresentano una comune rete di bassa tensione dell'isola, perciò l'indagine mira a valutare l'impatto dei VE, evidenziando differenze e somiglianze tra le due reti. A partire da dati statistici relativi al comportamento alla guida della popolazione danese, modelli realistici di carica dei VE sono designati implementando diversi livelli di penetrazione dei VE e potenza di carica. Le due reti sono inizialmente analizzate con la topologia e i consumi di carico delle reti esistenti, dopodichè diversi scenari di penetrazione dei VE sono testati mediante l'analisi di load flows. La larga penetrazione dei VE può causare problemi di affidabilità nella rete elettrica, perciò dopo le varie analisi tecniche, l'utilizzo dei VE è analizzato come componente flessibile per il sistema elettrico ed il suo mercato. Tale analisi mira a massimizzare i vantaggi dei tre principali protagonisti: sistema elettrico, gestore del sistema di distribuzione e consumatore. Questa tesi si basa su dati reali (alcuni direttamente misurati, altri elaborati) con lo scopo di creare uno scenario realistico come progetto pilota su piccola scala per studi futuri.

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NOMENCLATURE

Acronyms

AC	Alternating Current
AS	Ancillary Services
CAPEX	Capital expenditure
Ch-1ph	Single-phase charger
Ch-3ph	Three-phase charger
CHP	Combined heat and power
DC	Direct Current
DER	Distributed Energy Resource
DSO	Distribution System Operator
EV	Electric Vehicle
HV	High Voltage
LV	Low Voltage
max	Maximum
mean	Average
min	Minimum
MV	Medium Voltage
OPEX	Operating expense
p.u.	Per-unit
PF	PowerFactory
SOC	State-of-Charge
St.	Station
ToU	Time of Use
TSO	Transmission System Operator

Variables

$cos\phi$	Power factor
P	Active power
Q	Reactive power
Q_n	Nominal battery capacity
Q_u	Used battery capacity
S	Apparent power
t	Time
R	Resistance
V	Voltage
X	Reactance

1 INTRODUCTION

1.1 Background and motivation

As stated in the Paris agreement, the worldwide commitment towards solving the environmental problem needs the collaboration of the 195 countries, which agreed on limiting the average global temperature increase to less than 2^{o}C above the pre industrial levels [17]. The Kyoto protocol, the 20/20/20 agreement and other agreements are trying to keep together various countries in the fight against the same issue: global warming.
As part of the different agreements and in decision of achieving specific national goals, the Danish government has signed the *Energy Strategy 2050*, European commission's roadmap to a more sustainable, competitive and secure energy system [18]. The roadmap establishes some obligations for the Danish society to reach the CO_2 (carbon dioxide) neutrality in the energy sector, since it is the field with the main source of greenhouse gas (GHG) emissions.

The world societies are strictly interconnected with the energy sector, from daily use of a mobile-phone charger to house heating, everyone depends on different forms of energy.
As for the energy consumption, the worldwide demand for electricity is increasing in different ways around the world. The increase is more evident in the Non-OECD (Organization for Economic Co-operation and Development) countries, than in the OECD nations, where the growing demand is counterbalanced by energy efficiency improvements. The global electricity consumption in 2015 reached 20200 TWh, the average annual growth rate was 3.4% between 1974 and 2015, with a value of 6287 TWh in 1974 [19]. In the OECD countries the gross electricity production is distributed between different sources, whereas the Non-OECD production sources are mainly dependent on coal, around 47.1% in 2015 [20].
The progress on the electrical power generation, is the consequence of a constant request of reduction of GHG emissions. This demand encourages research to improve the efficiency of present sources and to move towards a system based on renewable resources, thanks to their lower production of CO2. As a consequence, the power system is becoming a mix of energy sources, which the same network has to actively integrate and hold together in the whole system.
The power system is constantly changing, and the growth of the renewable share of the power production increases the fluctuating production of the system, owing to the intermittent characteristics of these sources.

Stability and reliability are the two major features of the power network. The diversification of the resources is making maintenance of the two properties more challenging, as demonstrated by the increasing amount of blackouts experienced around the world [21]. Power outages have different forms - planned, unplanned, unanticipated faults and burnouts, but all results in the same electricity loss. Table 1.1 illustrates non planned power outages, which have involved $\geq$ 1000 people for at least one hour and at least 1 million (M) person-hours of disruption. It can be observed that the number is increasing:

Table 1.1: Wide-Scale Power Outages (Blackouts), data adopted from [13].

Year	Number of Blackouts	Larger Blackout
2017	12	1st March, New York and 5 other states: 10M affected
2016	4	7th June, Kenya (4hr blackout): 20M affected
2015	7	26th January, Pakistan: 140M affected.
2014	7	1st November, Bangladesh: 150M affected.
2013	9	22nd March, Belfast.
2012	6	31st July, India: 620M affected (biggest ever)
2011	14	24th Sept, Chile: 9M affected.
2010	9	14th March, Chile: 15M affected.
2000-2009	47	2001, India: 230M affected.
1990-1999	14	26th Dec 1999, France: 3.4M affected.
1980-1989	7	16th Oct 1987, interruption HV Cross-Channel UK-France.
1970-1979	6	13th July 1977, New York: 9M affected.
1960-1969	2	5th Aug 1969, Florida: 2M affected.

The power outages are increasing year by year, mainly caused by severe weather, especially in U.S. [22]. These events are costly for the grid operators and the societies, therefore various strategies for modernizing and improving the grid resilience have to be considered.

Transmission and distribution system operators (TSOs and DSOs) take care of the network, the former deals with generation and transmission, whereas the latter is responsible for the connection from transmission to final consumption. With the integration of renewable sources, the monitoring of the power system is changing. In the past the power was flowing from large generators to the loads, today the power can flow in the opposite direction as well. This requires more data exchanges between the components of the system, increasing the difficulties to monitor the whole network from DSO's and TSO's perspective. In the past, the main objective of the electricity suppliers was to supply power meeting the demand. Today, due to the integration of renewable sources in distributed grids, the power can also flow from the local production to the grid. In this new reality, large-scale plants are not the main producers of the system and they have to increase or decrease their generation depending on the distributed renewable resources, acting as a bridge for the gap between local, production and consumption. This takes place because of the environmental friendly characteristics of the renewable sources, preferred above the fossil-dependent ones. For example renewable energy can contribute to social and economic development, to accelerate the access to energy for the billion people without electricity, limiting the GHG emissions.

In Europe this is becoming reality, since the European Union (EU) is trying to encourage cooperation and investments to embrace renewables and avoid fossil-dependent resources in all energy sectors. The new European policies, funding opportunities and incentives are driving the communities towards a modernization of the use of energy, that aims to cover: energy efficiency, increase of renewable energies, fair deal for consumers. The use of renewable sources requires a well-interconnected European power system, and even though the European grid is the most secure in the world, many investments are still necessary to improve the interconnection security [23].

The society is energy dependent and a similar strong correlation can be observed between society and transportation. Humans have always been using different transportation systems, from riding animals to sailing vessels. Today many kinds of transportation are available and in most western countries everyone can own a private vehicle. In Europe the amount of cars are increasing. On average there are circa 500 cars per 1000 inhabitants, but there are differences between countries depending on the necessities of the societies and the government regulations. For instance, in 2015 Denmark counted circa 410 cars per 1000 inhabitants, whereas Italy, above-average, had circa 610 cars per inhabitant [24]. On the subject of the environment, transportation has a relevant role. The transport sector produces 25% of the worldwide CO_2 emissions, and in addition this sector is rapidly growing, bringing along its negative effects [25]. Figure 1.1 shows the EU-28 [1] greenhouse gas emissions broken down by the main source sectors. In 1990 the transport sector was responsible for 15% of the emissions, whereas in 2015 the percentage increased to 23% of the total emissions. In both cases this sector is the second largest source of GHG emissions.

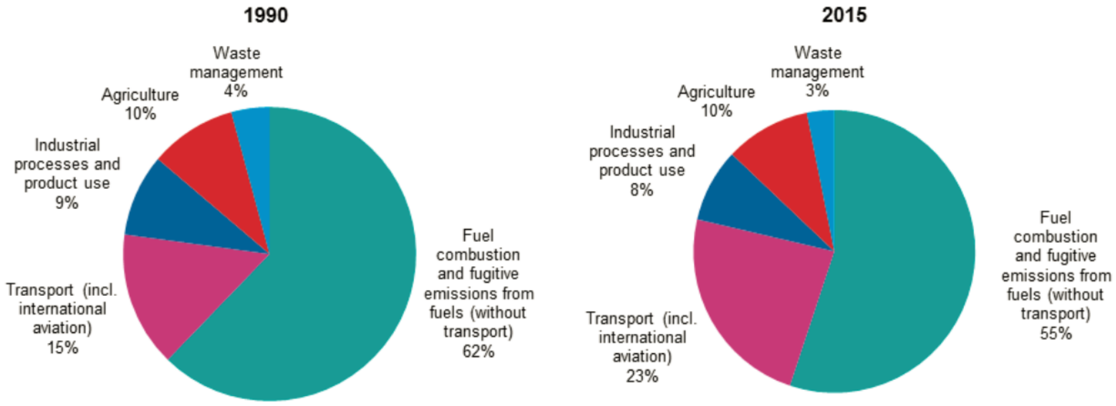


Figure 1.1: Greenhouse gas emissions, by source sector, EU-28, 1990 and 2015 [3].

In this context, the electric vehicles (EVs) have gained importance as a possible asset to decrease the emissions and to achieve a reduced fossil-dependent transport sector.
As new load for the power system, the EVs impact the distribution system network in several ways, not only as unpredictable charging pattern of the individual EV, but also as consumption increase of the sum of EVs.

According to data from the World Bank, in 1970 the world electric power consumption was 1199 kWh/capita per year and in 2014 it was 3126 kWh/capita. In 40 years the consumption per capita grew circa 3 times, but what would happen with the integration of EVs?
Considering a single family house, the integration of an EV causes a significant increase in the electricity consumption. The impact on the power system depends on the amount of EVs, on their characteristics and on possible constraints the grid and EVs have.
Various ongoing project[2] on the topic aim to understand how to integrate the EVs in the

[1] The EU-28 is the abbreviation of European Union (EU) which consists of 28 member states.
[2] Some ongoing/proposed Vehicle2Grid (V2G) pilot projects in Europe are Parker, ACES, Denmark V2G. More projects can be found in [26].

network in an active way.
Figure 1.2 shows the electric car stock growth from 2010 to 2017 in the Nordic region - Denmark, Finland, Iceland, Norway and Sweden -.

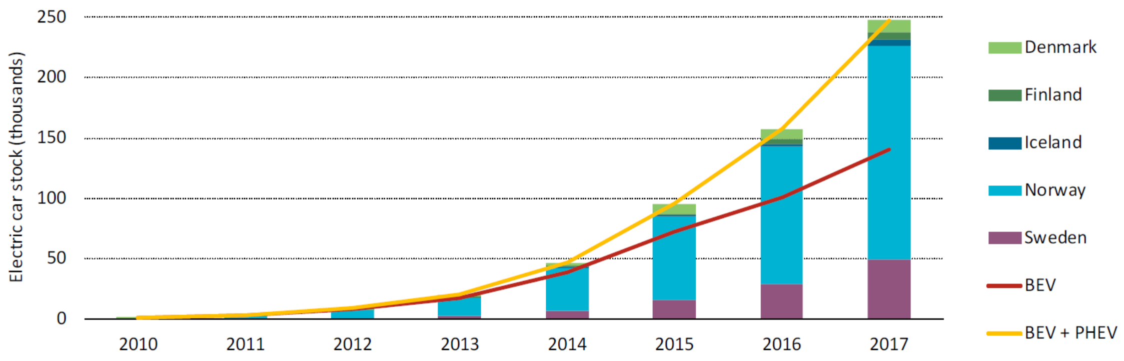


Figure 1.2: Evolution of the global electric car stock in Nordic countries, 2010-17 [4]. BEV stands for Battery Electric Vehicles, PHEV for Plug-in Hybrid Electric Vehicles.

The Nordic countries are the third largest market of EVs by sales volume in the world after China and the United States (U.S.). Norway has the leading role between the Nordic regions, with every 16th car being an EV and the Nordic average is one out of 50 cars. Globally speaking, the electric cars corresponds to just 0.2% of the total number of vehicles in circulation, even though the EV market is growing. To represent a significant change in the amount of CO_2-emissions and in relation to global warming, EVs still have a long way to go [27].

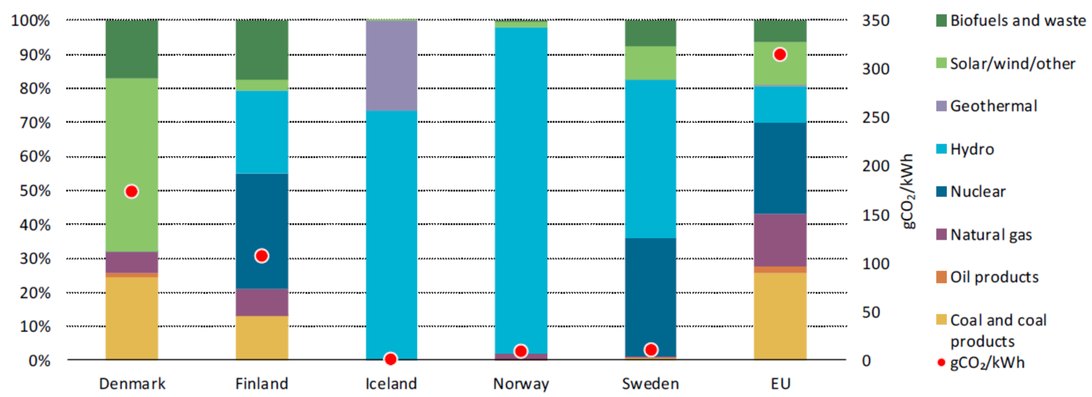


Figure 1.3: Power generation mix and CO_2 emissions per kWh by country and EU average in 2015 [4].

Considering the global warming impact, it is important to mention that EVs are not completely carbon free, since the electricity used for charging can be produced using renewable or fossil fuel dependent sources. Figure 1.3 illustrates the power generation mix, the CO_2 emissions per kWh by Nordic countries and the EU average, in 2015. The large generation from renewables in the Nordic countries is compared with the power generation mix in Europe, which on average is more carbon dependent.
Although the differences in electricity production, in terms of CO_2 emission the EVs are always preferable to vehicles powered by ICE's (internal combustion engines). Considering the Danish electricity production mix, the emission of an EV is equal to 40.4 gr/km, whereas

a diesel car produces circa 105 gr/km and a petrol one circa 110 gr/km [28, 29]. The new petrol and diesel cars are annually decreasing their CO_2, CO and NO_x emissions due to stricter emission rules by EU. The nearest target defined by the European commission is in 2021, when the fleet average to be achieved by all new cars is 95 grams of CO_2 per km [30]. Some monetary penalties are already applied and will continue to increase for the manufacturers that exceed the emission limits, closing the expenses gap between conventional cars and EVs. In Denmark, due to the high taxes applied on domestic electricity, the price per km of EVs and conventional cars are comparable: 0.44 DKK/km for the former (an EV drives circa 5 km/kWh) and 0.4 - 1 DKK/km for the latter [29].

The transport sector plays a significant role, since the integration of EVs would impact not only on the society, but also on the power network. The power system could benefit from the integration of the EVs as a resource for the distribution grid. To this end, the EVs have to cooperate with the existing network in an active way, to find the appropriate meeting point between the benefits of system, aggregator and user.

This thesis aims to understand the technical impact of realistic EV penetration scenarios on the grid. Moreover, the EVs are integrated in the power system as service support, to determine the potential techno-economic benefits for the power system, aggregator and user. The analysis is carried out using real household consumption data and grid characteristics.

1.2 ACES project

This thesis has been completed in collaboration with the ongoing project ACES (Across Continents Electric Vehicle Services). This project is part of the Center for Electric Power and Energy / DTU Elektro's project portfolio, conducted by the project leader Mattia Marinelli.

In addition the project has been undertaken in collaboration with the Japanese and UK based research centers of Nissan, which allowed a comparison between the Danish study case and existing electricity market services in the UK and Japan.
The ACES project is built upon a strong partnership with Bornholm Energi & Forsyning (former Østkraft), which is fundamental for this thesis and the whole project, as it has made real local data available for use and gives a potential to test the outcome of the project in practice.

The ACES project is built on top of previous researches, such as the Nikola project [31] and the Parker project [32]. As partner of the two cited projects, NUVVE - electric vehicle (V2G) aggregation service provider - is collaborating with the ACES project, providing technical support and expertise on aggregation services.

The ACES project intends to investigate technical and economic impacts by EV integration in the power grid of the Danish island of Bornholm, considering the EVs as contributors to guarantee a reliable and cost-efficient power system operation with a high share of renewable energy sources. To prove the EV techno-economical functionalities, the project analyses a full-scale penetration scenario of EVs and a small-scale pilot project, involving up to 50 EVs and V2G chargers. Thanks to the partners involved in this project, ACES compares existing electricity market services with two other countries: United Kingdom and Japan. More info about the project can be found in [1].

1.3 Thesis objectives

The thesis deals with the EV penetration topic. First as a technical concern for the DSO and second as a technical-economic opportunity for the network and the market players, aggregators and users. The studies of this project are performed on two residential low-voltage grids of Bornholm. Although European low-voltage power systems and markets have differences, the methodology and analysis of this model can be used as small scale pilot project for future studies.

The main project question is: **how can EVs be actively integrated in the electrical power distribution network maximizing the benefits for system, aggregator and user?** To this end, the learning objectives with the respective sub-questions can be summarized as follows:

- **How can EVs charging pattern be simulated based on the national travel survey?**
  Considering the worst case scenario and the specific type of battery, the charging pattern of the EVs is usually determined looking at the characteristics of the battery and the charging current limits. It is valuable to analyze how the human behaviour and driving pattern influence the charging pattern of the EVs and how the distribution system is, in turn, involved.
- **What are the impacts of different penetration levels of EVs on the distribution network of Bornholm?**
  It is important to analyze how the EV penetration impacts on low-voltage grids with different loading and customers' characteristics. In the near future, the penetration of the EVs could spread very fast. Various scenarios with different rated charging powers and increasing penetration levels - 25%, 50%, 75%, 100% - will be analyzed to evaluate the consequences on the power system and to determine, when and how, the DSOs need to take action. Furthermore, the various penetration levels increase the total load of the system, causing a grow in distribution losses, congestion and under-voltage issues. This fact is strictly linked to the DSO role, passing on technical issues and economic expenses.
- **Which value can the EVs, as a flexible active component of the distribution system network, create for the system? How should it be remunerated?**
  The EV active contribution with the DSO grid responsibilities is of mere existence for a system with high EV penetration level. The procurement of flexibility by EVs in the electricity system influences the electricity market. This is made possible changing the charging patterns of the EVs. In order to define a smart integration of the EVs, an economic analysis is implemented to determine how the EVs can benefit power system, aggregator and user.
- **How could taxes/tariffs or regulations be used to incentivize the smart integration?**
  The EVs interact with the electricity market that, as every kind of market depends

on different taxes/tariffs/regulations present in each nation. Market changes can play a critical role for the EVs growth in the society. An investigation of the ToU tariffs, and EV subsidies is made and the impact of the 100% EV penetration in the two analyzed feeders is pointed out.

1.4 Thesis outline

This thesis is based on the aforementioned objectives organized in seven chapters. Starting with an introduction of the role of the EVs in the power system, moving progressively to the model implementation and the techno-economical analysis. Finally, the main results are summed up and discussed to reach some conclusions and to give suggestions for future work. A short description of each chapter can be read below, and at the end of each chapter a summary can also be found:

- **Chapter 2** is structured as follows. The first section gives an overview of the power system, with challenges and analyses of TSO and DSO responsibilities. The second section focuses on an overview of the electricity market. Follows a description of the evolution and new regulations regarding smart meters, ToU tariffs and role of EVs.
- **Chapter 3** begins with an overview of previous results on the EV penetration topic. Then the Danish National Travel Survey data are analyzed, and based on these data the EV charging pattern model is implemented.
- **Chapter 4** begins with an overview of the electricity system of Bornholm. Then the two Danish LV feeders' configuration of Tejn and Rønne are investigated. The households and fast chargers' consumption is analyzed in detailed.
- **Chapter 5** contains the model implementation of the households, fast chargers and domestic chargers in PowerFactory. The simplifications due to software limitations are described. Finally a control strategy to enable flexibility procurement by EVs is described.
- **Chapter 6** contains the technical results and sensitivity analysis of the two study cases. An introduction of the power quality parameters is given, then followed by the investigated scenarios. The two feeders, Tejn and Rønne, are firstly studied with their current configuration. Afterwards, various EV penetration scenarios are implemented considering different rated charging powers and level of penetrations. Finally the chapter is concluded with a sensitivity analysis.
- **Chapter 7** describes the economic analysis. The conventional grid reinforcement solution to congestion issues is compared with the EVs provision service enabled by the DSO. Finally the economic benefit of the ToU tariff is investigated as economic benefit for the EV owners.
- **Chapter 8** concludes the thesis, answering to the research questions in Chapter 1 and pointing at future work.

This thesis contains technical and economic information, mainly focused on Danish real data, aiming to create a realistic and feasible scenario as a small scale pilot project for future studies.

2 The electric vehicles in the evolving power system and market

This chapter gives an overview of the power system and market actors and interconnections, comparing traditional and future grid configurations. In this light the role of the EV penetration in future grids is pointed out. Furthermore smart-meters, time-of-use (ToU) tariffs and new regulations are analysed to give information about the state-of-art of the power system and, as far as possible, to be used by the author during the technical and economic analysis of the thesis.

2.1 The power system

2.1.1 General characteristics

The electric power systems are constantly under development. In 1882, the first complete electric power system of Thomas Edison was a direct current (DC) network, with only 59 customers in a 1.5 km area. In the 1890s, the alternating current (AC) system won the "War between AC and DC", thanks to its ability of step up and down to different voltage levels, and to the flexibility and simplicity of the AC components. The electric power systems have always had two main goals: first to convert energy from the available form - chemical, wind, solar, etc. - to the electric form, second to transport the electricity from the production point to the consumption one. The interest of the customer is to use power from the socket when he wants, and, if possible, with minimum costs. The national grid codes and standards define some indexes to represent the quality of the supplied power:

- voltage level: for customers connected to low voltage (LV) grid, the voltage is ensured to be 230 $\pm 10\%$ at the connection point. The same percentage is applied to higher voltage levels.
- system frequency: in the European countries the frequency is limited to 50 $\pm 0.1\%$ in normal operation.

Today the electric power systems can be very different in size and components, but all of them are composed of three parts: generation, transmission and consumption. The AC systems are three-phase grids, operated at constant voltage. The generation of electricity is mostly done by the synchronous machines. The transmission network can be divided into transmission, sub-transmission and distribution systems. Voltage levels, distances and interconnected systems are the main differences between the transmission subsystems. The consumption is the final stage of the power system, when the power is individually consumed by the users [33]. The described basic structure of the electric grid can be observed in Figure 2.1.

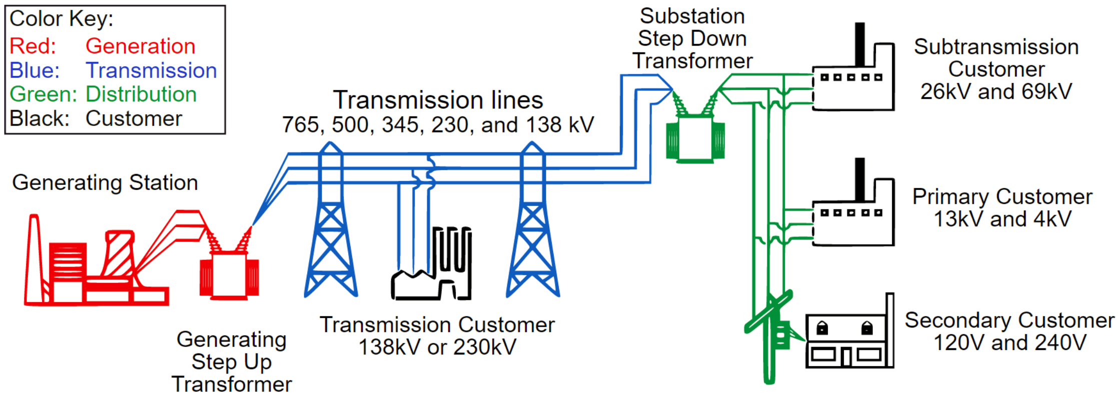


Figure 2.1: Basic Structure of the Electric Power System [5].

Until the 1980s the electric power system has always been a monopoly, controlled and owned by the government. The traditional grid was characterized by power flowing from large generation units to customers of different sizes. In the early 1990s, the liberalization and privatization of the electricity industry brought about changes in the power system. The European liberalization is an ongoing process that aims to create a common market where every consumer can buy electricity from any producer. Due to the nature of the electricity as essential commodity, various difficulties were met to approach the liberalization, not only political, technical and economical, but also symbolic and cultural [34]. Even though this competition between electricity producers and sellers, the two main grid operators, TSO and DSO, remained centralized as their initial form.

The *TSO* is the entity responsible for the electricity transmission system, if necessary maintaining and improving the power system. It has to provide and operate the high voltage (HV) networks for long-distance electricity transmission, keeping a balance between generation and consumption. To maintain the operational security, the ancillary services (ASs) are used by the TSO to preserve the power balance of the interconnected transmission systems. For example a part of the ASs are used to maintain the power system operation at a nominal frequency [7, 35].

The *DSO* is the entity responsible for distributing electricity, operating, maintaining and developing medium and low voltage networks. This entity directly provides the end-users, covering energy losses and reserve capacity in the power system [36, 37].

The boundary between TSO and DSO, is a transformer, namely TSO-DSO transformer. Today, due to the increasing amount of DER in the distribution grid, *TSO-DSO* interaction is needed. The DER are resources difficult to predict and control, therefore to maintain balance between generation and power demand, a collaboration between TSO and DSO is essential. The TSO is the generation-transmission part, the DSO controls the distribution-consumption connection, but now, due to the DER integration, the interaction is changing into a distribution-consumption-"generation" connection.
Figure 2.2 shows a comparison between traditional, present and future configuration grids, respectively. In the future grid configuration, not only the exchange of data between TSO and DSO is expected to increase, but also between DSO and users.

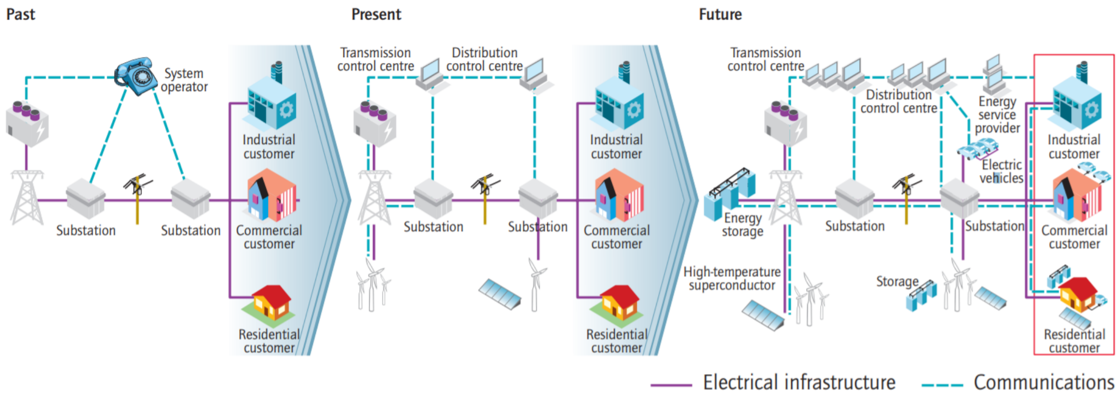


Figure 2.2: (a) Past - (b) present - (c) future - configuration grid [6].

2.1.2 The Danish power system

The Danish power system is split into two synchronous areas: DK1 is the western area, connected to the European continent, DK2 is the eastern are, part of the Nordic synchronous zone. The Nordic area includes Denmark, Norway, Sweden and Finland. Therefore DK1 follows the ENTSO-E Continental Europe Operation Handbook legislation, whereas DK2 operates according to the Joint Nordic System Operation Agreement.

Energinet is the TSO, independent public entity owned by the Danish state. Energinet requirements are to maintain and to operate the high-voltage grid, by ensuring security of supply using activities, such us ASs.

In 2016, 61 Danish DSOs were counted. Their activities act on the distribution part of the power system, fulfilling the grid constraints about loading and voltage, see Figure 2.3:

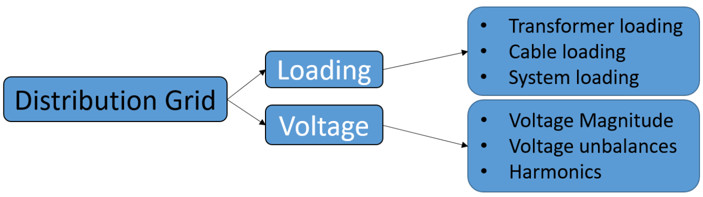


Figure 2.3: Distribution grid constraints to be solved by DSO. Adapted from [7].

Considering the consumer's need, to maintain and organize the power system, the Danish final users are divided into three groups, according to the voltage level of the distribution network to which they are connected, see Table 2.1:

Table 2.1: Group of customers and voltage level in the Danish electricity sector, according to [14].

Group of customer	Voltage level connection
A-Customer	60-30 kV
B-Customer	20-10 kV
C-Customer	0.4 kV

Depending on the voltage level, rights and obligations of the users are different as well as

electricity prices. Based on the Waterfall Principle, the customer pays the expenses of the network used to deliver electricity to them, including substations costs and administrative issues. The transmission grid tariffs are equal for all customers [1], differently the distribution grid tariffs are charged to the customers corresponding to the voltage level price. On top of the tariffs, the customer pays for the amount of used electricity, accordingly to one of the following market options: 1. fixed price product, 2. variable or spot price product, 3. product from renewable sources [12].
This thesis deals only with C-Customers, since the analyzed feeders are two LV grids with customers connected to the system through 400 V.
For more information about the Danish electricity price of different customer levels see *elpris.dk*.

More information about the Danish distribution power system, for the specific case of the island of Bornholm, are given in Chapter 4.

2.2 The electricity market

2.2.1 General characteristics

The growing electricity demand, the increasing share of renewable energies, the high oil price volatility, are some of the factors making the electricity markets always more interesting. The electricity demand is different from other goods, due to the fact that shifts in demand are not always associated with price changes. TSO and DSO are natural monopolies subjected to national network regulations. Electricity generators and suppliers are part of liberalized markets, where customers can freely choose their own electricity supplier. The European electricity markets have two main parts: the wholesale market and the retailed market. The wholesale market is the competition between generators, which offer their electricity production to suppliers or large consumers, that in their turn purchase goods to sell it further. On the other hand, the retail market is the possibility of end-users to choose between competing electricity retailers.

Considering the interest of this thesis in the Danish contest, a more detailed overview of the Nordic wholesale and retail markets is given below.

2.2.2 Nordic Wholesale and Retail Market

The Nordic *Wholesale Electricity Market* has a main physical settlement traded in the Day-Ahead market (DAM), afterwards the intra-day market regulates the final exchanges until one hour before the production time, giving time to the balancing market to reduce imbalances between scheduled bids of DAM and real time supply and consumption.
The interconnection between balancing market and imbalance settlement is a responsibility of the TSO. Since Denmark is part of the Nordic synchronous zone and Nordic electricity market, the entity responsible for the wholesale market is Nord Pool, Nordic Power Exchange owned by Energinet and the other Nordic TSOs [12, 38].

The *Retail Market* is locally operated. The electricity suppliers make their offers and the consumers can choose the offer they prefer. In 2003, in Europe the full liberalization was

[1] There are some exceptions for self-consumers.

introduced in the retail market, aiming to increase competitiveness between the products, to achieve sustainability targets and to develop security of supply provision. In the Danish market there are 33 electricity suppliers, Ørsted [2] covers alone 21% of the whole market.

2.3 Changes and new regulations

2.3.1 Smart metering

As aforementioned the increasing amount of DER in the distribution grids requires a TSO-DSO interaction. Sharing data is the base for TSO-DSO collaboration, to ensure long-term benefit to the consumers. In this context, the European (EU) *Third Energy Package* established the requirement of the intelligent metering systems for all the Member States. At least 80% of the customers must get the electricity meters by 2020, fulfilling the minimum requirements seen in Figure 2.4.

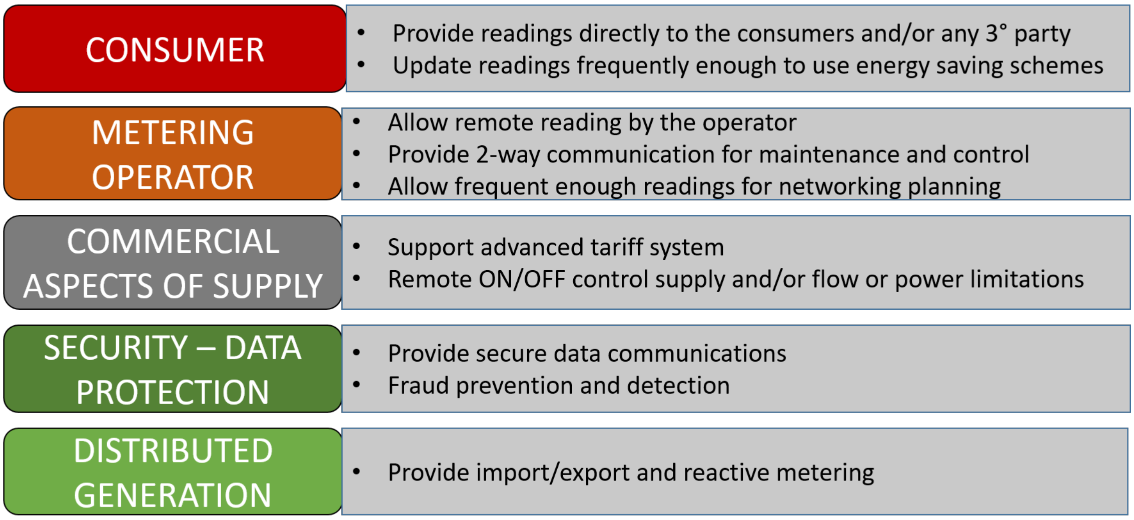


Figure 2.4: List of minimum functional requirements that every smart metering system for electricity should fulfill (2012/148/EU Recommendation) [8].

The Danish electricity companies are following the EU regulations, indeed today there are already 1.63 million metering points with an installed smart meter. In June 2013, the Minister for Climate, Energy and Building established that the DSO is responsible for the installation of the smart meters from 2014 to 2020. The minimum functionalities of the Danish smart meters are the same as the ones proposed in the EU Recommendation 2012/148/EU, as in Figure 2.4.
Smart metering provides readings every 15 minutes with detailed information on customers energy consumption. The smart meters can be used to inform consumers and to identify cost effective options for energy savings. Based on this, DSOs and electricity suppliers can create new business opportunities for investments in energy savings [40].

[2]Initially called Dansk Olie og Naturgas A/S (DONG), meaning Danish Oil and Natural Gas. In 2017 the energy company decided to sell its oil and gas business and to change its name to Ørsted. It is the largest energy company in Denmark and it is based in Fredericia [39]

It can be concluded that the smart meters are not a solution to specific problems in the power systems, but thanks to their characteristic of measuring consumption data, they can be the tool for the management of future systems.

2.3.2 Time-of-use tariffs

The total electricity consumption of a country is known to be differently distributed during a day long period. Usually two peaks occur, one in the morning and one in the late afternoon, if the consumption is too high, the distribution power system can experience overloading of transformers, cables, and under-voltage problems.
The time-of-use (ToU) tariffs are one of the used methods to encourage consumers to move their consumption from peak consumption periods to off-peak periods. The electricity price has a very little influence on the electricity tariff, since the electricity tariff mainly reflects the costs of operating the system. For this reason the time-variant pricing acts on the electricity tariff, to encourage a more efficient resource distribution.

In the late 1970s, the first electricity pricing experiments were carried out in the U.S. and in Canada. From the beginning it was shown that customers respond to higher prices during the peak periods by reducing their consumption and/or shifting the electricity use to less expensive off-peak periods. The studies showed similar results between the countries, but also varieties due to climate differences and use of diverse appliances by the owners [41, 42, 43, 44].

In Europe few countries adopt ToU tariffs. In Italy the ToU tariffs were firstly applied in 2007. The diversification of the electricity tariffs were imposed to Italian consumers connected to the LV grid with a smart meter. Even UK, Spain, Portugal, France, started to use diversified tariffs around 2005, but due to lack of smart meters, the development of the tariffs was slowed down and the effects were difficult to be observed. In 2017, in Denmark the power distribution company Radius [3], applied new rules to its consumers connected with 400 V in the DK2 network. With the replacement of the old meter with the smart meter[4], the tariff was diversified in two periods of time:

- High load: all days from October to March from 17:00 to 20:00
- Low load: the rest of the time.

The difference between the two periods is a tariff increase of circa 50 øre/kWh during the high load period [45].
Considering an average family consumption of 4000 kWh per years [46], 183 days (from 1st October to 31st March) of applied ToU tariffs, the savings per year of different reduction shares of consumption are quantified in Table 2.2.
In January 2012, between 18:00 and 19:00 the Danish households consumption accounted for circa 35% of the total electricity consumption [47], thus the energy consumption between

[3]Radius is the Danish power distribution company owned by DONG Energy. It was renamed from DONG Energy El Distribution to Radius Elnet on 1 April 2016 and was given its own distinct visual identity to make it easier for Danish customers to distinguish between the power distribution company and the rest of DONG Energy. More info can be found in [39].

[4]If the old meter was replaced with a smart meter before the 1st December 2017, the consumer had a change in its tariff before the 1st February 2018. If the meter was replaced after the 1st December 2017, the hourly rates were applied circa 1-2 months after the change of the meter.

17:00 and 20:00 is here considered to account for 50% of the Danish daily consumption. The consumed energy by an average family for 183 days from 17:00 to 20:00 is evaluated as in equation 2.1:

$$E_t = \frac{4000kWh}{365d} * 50\% * 183d = 1003\ kWh \tag{2.1}$$

The moved energy consumption (E_m) is defined as in equation 2.2:

$$E_m = E_t * perc \tag{2.2}$$

with *perc* the percentage of the moved consumption considered in Table 2.2. The savings are:

$$Savings = E_m * s \tag{2.3}$$

where s=50 øre/kWh.

Table 2.2: Total savings per year for an average family with different shares of moved consumption from peak to off-peak period.

perc [%]	E_m [kWh]	Savings [DKK/year]
100%	1003	501.5
75%	752.3	376.1
50%	501.5	250.8
25%	250.8	125.4

These values are calculated moving the consumption from the peak hours to the off peak hours with saving of 50 øre/kWh. In the first case, moving 100% of the consumption the maximum saving is 501.5 DKK/year. Loads can be divided into two categories: the first represents the loads that can be moved in time, for instance the washing machine, the second represents the loads characterized by cycles of continuous operation, such us freezer, fridge etc.. Due to the different load categories, the scenario with 100% moved consumption is unrealistic.

A Italian study analyzed 4 different types of ToU tariffs. Moving 100% of the movable loads and only 20% of the non-completely movable loads, the study has shown that the 25% of the total amount of consumption can actually be shifted. Similarly to the Danish values calculated in Table 2.2, the Italian yearly savings are not high enough to encourage the consumers to move their consumption to the off peak hours. Furthermore, the study showed that circa 60% of the analyzed consumers moved their consumption to save money, decreasing the peak residential load with maximum 15-20%, which scaled to the total load of the country gives a reduction of maximum 4-5% [48].

In the Danish case, the data from the ToU tariffs applied to the C-customers are not available yet, nevertheless there is a first feedback from the ToU tariffs applied to the B-customers (see Table 2.1) in 2012 by DEE (DONG Energy Power Distribution A/S). The analysis showed that the differentiation of the tariff is a potential tool for shifting consumption from peak to off-peak periods. The tariff for B-Customers was divided into: low (night and weekend) with 15 øre/kWh, normal (daytime working days) with 19 øre/kWh, peak (morning and afternoon peak hours) with 22 øre/kWh. The comparison of 480 large customers between the consumption in 2012 and the one in 2011, showed a reduction of the peak load consumption of 1.1% [49].

A Danish experiment called "Move!" analyzed 1050 customers randomly selected in the Danish DSO SEAS-NVE [5] grid for 12 months, from 1st April 2014 to 31st March 2015. The idea was to evaluate how ordinary households without electric heating would change their consumption behaviour when time-differentiated tariffs are substituted to the fixed ones. The customers were split into two groups: a control group with a fixed tariff and a test group with a test tariff (low, high and peak prices). The test group showed a peak load reduction of circa 2% in comparison to the control group, even though the total electricity consumption was not influenced. The results highlighted only short time effects, the long time effects are still unknown. Having the same amount of daily consumption, the peak hour load of the test groups was actually moved to the off-peak time, showing a "kick back" effect from 20:00 to 21:00 [49].

Although countries and years of implementation are different, the similar results demonstrate larger reduction of peak consumption when the ratios between peak and off-peak electricity prices is higher, even though the daily energy consumption is kept constant.
Summing up, time-of-use tariffs are usable tools to encourage costumers to save money and, in the same time, to decrease the peak load consumption. Nevertheless, the effect of diversified tariffs depends on different and uncontrollable factors, such as the human behaviour, thus there are no numbers to define the amount of customers that would always move their consumption to follow the lower price. In this context the smart meters pop up, as tools for recording consumption data. In some years precise data about the household consumptions will be available and they could be used to define more appropriate ToU tariffs and to quantity their effects in the power system.

2.3.3 Grid code technical regulations and battery requirements

Batteries are considered one of the possible tools to deal with the decentralized grid configuration, thanks to their possibility to store power wherever it is needed. In Denmark, a giant battery, with power output of 630 kW and energy capacity of 460 kWh, is located in Nordhavn, Copenhagen's sustainable urban district. The giant battery is used for different kinds of tests and researches, to create a baseline for future battery integration into power systems.

Due to the scarcity of battery plants, European regulations are not developed yet. Energinet grid code (Technical regulation 3.3.1 for battery plants), is one of the first documents for batteries at Europen level (ENTSO-E). This regulation came into force on the 23rd June 2017.
The regulation is analyzed in this thesis, since EV charging stations are included in the definition of a battery plant: "The battery plant definition covers both permanently and temporarily connected battery plants, including, for example, V2G electric vehicle charging stations. A battery may consist of several separate inverters and batteries.".

[5] SEAS-NVE Net A/S is the second largest DSO in Denmark and supplies approx. 400000 end-customers mainly in the the South-Eastern part of Denmark [50].

The battery plants are divided into different categories according to the power level:

- A1: up to and including $\leq 11kW$
- A2: above 11 kW up to and including 50 kW
- B: above 50 kW up to and including 1.5 MW
- C: above 1.5 MW up to and including 25 MW
- D: above 25 MW up to and including 100 MW

When a number of batteries is aggregated and connected to the same Point of Connection (POC), the rated power in the POC is the sum of the connected battery units, that function as one battery plant. The sum of the rated power in the POC determines the plant category and thus the requirements for connection. The Point of Common Coupling (PCC) is defined as the point in the public electricity supply grid where consumers are or can be connected. The POC is the point in the public electricity supply grid, where the battery plant is or can be connected. PCC and POC may coincide electrically, but the requirements specified in the regulation are applied to the POC.
Technical and functional minimum requirements of battery plants that are going to be connected to the Danish grid are specified in the regulation. The regulation gives also information about the services that the battery has to provide, showing higher requirements for higher power level connected. The Technical Regulation is divided into four sections: tolerance of frequency and voltage deviations, power quality, protection, frequency and voltage control. For each section, the characteristics and the constraints of the five categories A1, A2, B, C and D are specified. More info can be found at [51].

Storage has potential solutions to provide ASs and to solve unexpected and unpredictable problems of the grid. Since the battery is the main component of the EVs, the EVs are considered storage systems as well.

2.4 The role of electric vehicles

The electricity domestic consumption, without considering heat pumps and EVs has two peaks: one in the morning around 7/8 and one in the evening at circa 18/19. The EV penetration is expected to affect the evening peak consumption, because the majority of used power outlets is private and because people charge the EV when they come home from work. The charging outlets in the Nordic region for the EV electricity supply were circa 264000 in 2017, of which only 16000 were public. This matches with the consumers' preference, mainly on private electric vehicle service equipment (EVSE) [4].
As aforementioned the average consumption of a Danish family is approx. 4000 kWh/year. The introduction of an EV with an average driving pattern of 40 km/day is expected to consume approx. 3000 kWh/year[6], meaning that the family household consumption would almost double.

As a DER, the EV is not only a car for the owner, but also an active component of the power system. In Denmark the residential connection is usually three-phase (3-phase), nevertheless the EVs in the private buildings mainly charge on one phase, since the most sold EVs has a single-phase (1-phase) charger. This is due to the fact that in many countries

[6] Considering 5 kWh of average energy consumption per km.

the residential connection is 1-phase, therefore the manufacturing industries sell mainly EVs with 1-phase chargers. High EV penetration level could cause imbalances in the power system. Instead of increasing the problem, the EVs should be used as active tools to compensate the imbalances already present in the power system. A study demonstrated that enabling the selection of the lower loaded phase by the charging spot, the EVs can choose the phase and charge where the voltage is the highest (without changing phase during the charging time). In this case the EV becomes an active component of the power system balancing the imbalanced grid [52]. There are various services that can alleviate and/or anticipate the negative effects of the EVs on the grid, involving the control of the voltage and component loading. To reduce their impact on the power system, the EVs can be used as demand-side management, with a combination of load shifting through market mechanisms and user's response to price signals. If the EVs are not used for support service, the power system could have to deal with the negative effects of high EV penetration considering grid upgrades.

2.4.1 Electric vehicle background

The worldwide transport market is in constant growth. In 2016, an estimated 69 million private cars were sold worldwide, with increase of 3 million in comparison to 2014 [53]. Of the 69 million vehicles, the 1.14% (750 thousands) were registered as EVs [7], but only 0.2% were battery electric vehicles (BEV). Therefore there is still a long way to go for the EVs to make a challenge as part of the transport sector [27].

The electric vehicles can be categorized as follows [54]:

- Battery electric vehicles (BEVs) have a battery as the only energy source.
- Hybrid Electric Vehicles (HEVs) have gasoline engine and fuel tank, plus an electric motor, battery and controls. HEVs are not plug-in, as they can't be recharged from the power grid.
- Plug-in Hybrid Electric Vehicles (PHEVs) run on batteries and/or internal combustion engine. The battery can be recharged by plugging into the power grid or by the internal engine.
- Fuel-cell electric vehicles: run on electricity generated from hydrogen and oxygen in fuel cells housed within the vehicle.

This thesis deals with the first category BEV, that for simplicity is named in the rest of the thesis EV.

The EV market is trying to fulfill the consumer's demand to become competitive with the traditional cars: range, low cost, performance and efficiency are the basic wishes for personal transportation. During the last few years the most sold EV models in the U.S., Europe, Japan, and China in a random order are: Nissan LEAF, Tesla Model S, BMW i3, Renault Zoe and Volkswagen e-Golf. Their main characteristics are shown in Table 2.3.

[7] Only in this case the term "electric vehicle" includes: battery-electric, plug-in hybrid electric, and fuel cell electric passenger light duty vehicles. In the rest of the thesis, when speaking about "electric vehicles (EVs)" the author is always referring to battery-electric vehicles as they are the only one considered in this project.

Table 2.3: Comparison of the top-selling battery EV models, adapted from [7].

Brand	Model	Model year	Battery warranty (years)	Battery energy capacity (kWh)	AC charging power (kW)	DC charging power (kW)	Range NEDC* (km)	Range combined cycle EPA** (km)
Nissan	Leaf Visia	2015	5	24	3.6	50	199	135
Nissan	Leaf Acenta	2016	8	30	3.6	50	250	172
Nissan	Leaf	2018		40	7.7	50		240
Tesla	Model S	2015	8	85	10	120	502	426
BMW	i3	2014	8	22	7.4	50	190	130
Renault	Zoe	2015	5	22	43		240	
Volkswagen	e-Golf	2015	8	24.2	22	50	190	134

*New European Driving Cycle is defined in United Nations ECE R101.

**U.S. Environmental Protection Agency combined cycle is a weighted average considering 55% of the city consumption and 45% of the highway consumption.

In this thesis the new version of Nissan LEAF, with 40 kWh battery capacity, is considered [55].

The battery degradation of the Nissan LEAF is lower than other brands and models. For distance driven the battery energy capacity decreases with 10% every 50000 km (11% for the Kia Soul EV 27 kWh), but it is higher than the 4% battery degradation of the Tesla Model S. These values are important but also relative, since they depend on different causes - battery size, temperature, human behaviours, degree of acceleration etc. - [55]. The battery energy capacity is the main influence on the driving range, but as it can be observed in the table, there are two ranges, because the range depends on the definition of driving cycle. Indeed there is not a single interpretation of the driving range, since it is affected by the user's driving behaviour, external temperature etc.

In general, the EVs are more expensive than the equivalent traditional cars. For this reason, to cap the price, the most sold EVs are the ones with small/medium batteries. The battery represents up to 50% of the total cost of the EV [56]. The batteries for EVs have six major characteristics: energy (density Wh/Kg), power (kW), cost, life span (cycles), safety and performance. Today the most used batteries are the lithium based, as the ones in Table 2.3, mainly thanks to the good energy-to-weight ratio. Nevertheless they are still expensive, increasing the EV price, which in turn cannot compete with the traditional cars. The cost of the batteries is mainly dependent on the anode and cathode materials, which the price is constantly decreasing and within the next decade could make the price of the EVs competitive [57]. Furthermore, the simple structure of the EVs, without many movement components as in the traditional cars, is a potential factor for the EVs to become cheaper, not only as initial price, but also as maintenance costs.

As shown in Table 2.3, each EV model has a standard DC and/or AC charging power characterized by the power capacity. Three main features are used to characterize the charging:

- the charging level is the power capacity;
- the type of a charging station describes the actual used connector;
- the charging mode describes the safety communication protocol between the EV and the charging station.

Considering the three mentioned characteristics, the charging stations are divided into four groups: devices installed in households, slow EV chargers, fast EV chargers (public) and ultra-fast/high-power EV chargers (not yet deployed). According to the IEC 61851 standard, the most common power rates for domestic and public charging are:

Table 2.4: Charging power rates [15]

AC current	AC voltage	Grid connection	Power
10 A	230 V	1-phase	2.3 kW
16 A	230 V	1-phase	3.7 kW
32 A	230 V	1-phase	7.4 kW
16 A	400 V	3-phase	11 kW
32 A	400 V	3-phase	22 kW

In this project two kinds of charging power rates are considered: 3.7 kW and 11 kW.
In the rest of the report, the first kind of chargers is called Ch-1ph as single-phase chargers, whereas the second one is named Ch-3ph as three-phase chargers.

2.4.2 Incentives and subsidies for electric vehicles in Europe

Large scale production is the key for achieving cost reduction of EVs, and the current status is not yet able to encourage customers to prefer EVs over traditional cars. Government incentives or/and subsidies are the methods currently used to reduce the EV purchase cost and cost of ownership to compete the prices of the traditional cars. From the exemption of the monthly vehicle tax in Austria, to the 10-years exemption of the annual circulation tax in Germany, the European countries apply different tax incentives to EVs. Some nations are granting an incentive for the purchase of new EVs. For example in France the EV customers receive an incentive of 1000-6300 euro depending on the CO_2/km emitted, in Germany and Sweden an incentive of 4000 euro is given to consumers that buy pure EVs. Figure 2.5 gives an overview of support policies for EVs in the Nordic regions in 2017.

In Denmark the registration tax[8] for traditional cars is more than 100% of the initial cost of the vehicle, much higher of the European average of circa 20%. Thus the exemption from paying the registration tax until the 2015 gave high possibility to the EV market to grow. In 2016, the government decided that the EV users must pay the registration tax starting from 20% of the full registration tax in 2016, increasing to 40% in 2017, 65% in 2018, 90% in 2019 and 100% in 2020. This new regulation caused a decrease on the EV market sales. Thus to keep enlarging the EV market, a deduction based on battery capacity was introduced in April 2017 and the registration tax was decided to be fixed to 20% for two more years or until reaching a threshold of 5000 new registrations. For what concerns the circulation tax[9], the EVs pay the minimum amount of the traditional car tax, which are differentiated and based on fuel consumption and weight.
Another incentive used in Denmark for the deployment of the EV chargers regards the charging points: the public charging points pay 50% less of the power connection fees, whereas for the private connections the homeowners deduct the installation cost from their

[8] Tax on acquisition.
[9] Annual tax on ownership.

income tax. Last but not least, in 2017 the Government of Denmark decided that until 2020, consumers that charge at home receive a tax rebate of 0.94 DKK/kWh, meaning that the final electricity tariff is almost halved [4].

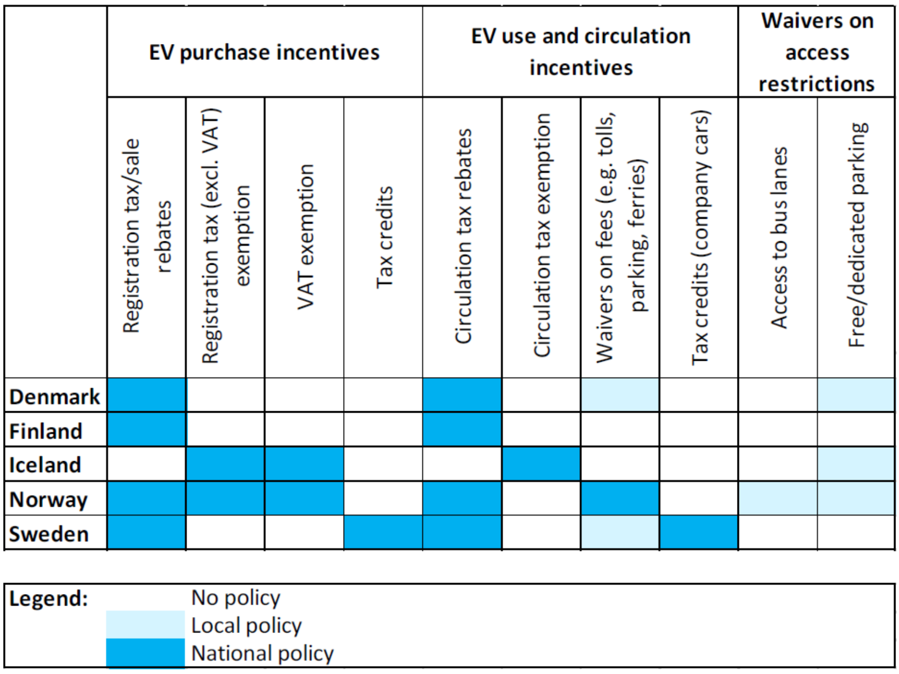


Figure 2.5: Overview of support policies for EVs in the Nordic regions in 2017 [4].

As shown in Figure 2.5, different forms of incentives are used to encourage people to prefer EVs over fuel cars. For instance in Norway the EV drivers are allowed to use the bus lane, in big cities, such as Oslo. Nevertheless, a Norwegian survey (named Elbilforening) proved that money savings is the most appreciated support policy for consumers, indeed 67% of the interviewers said that the economic benefits was the main reason to buy an EV.

2.5 Summary

An overview of the electricity system has been given in this chapter. First, the evolution and main actors of power system and market were investigated. Then, the focus was put on smart-meters, ToU tariffs and EV role, analyzed as important tools in a power system that is evolving and is going to be more and more interconnected. Thanks to their high quality measurements, the smart meters are important tools, not only for the management of the power system, but also for the customer, to control his own consumed energy. By reason of the smart-meters, the ToU tariffs are becoming achievable in this day reality, opening interesting research questions with the goal of determining the most appropriate tariffs from the power system and customer' perspectives. Finally, an overview of the EV state-of-art was given, pointed out the role of the EVs in the market, and the importance of economic incentives and subsidies to encourage the EV sales growth.

3 Electric vehicle charging pattern modelling

Some of the studies about EV penetration, consider the EVs with a simplified charging pattern, but this might lead to inaccurate results. The purpose of this chapter is to create realistic charging patterns, considering the battery characteristics, driving pattern and charging behaviour of the users. Firstly the chapter analyses the data available by previous study cases and the Danish national travel survey. Afterwards the chapter describes the EV charging pattern model proposed in this thesis.
Most of the statistics are based on data from traditional vehicle owners.

3.1 Previous results

This section aims to analyze the users driving behaviour, to understand when the vehicles are driven during the day and when not. The second period of time can be called "available hours", because the EVs can be charged, or used to procure flexibility services. The available time is usually longer than the needed time to charge the battery, therefore for the remaining time the battery could be used to provide services, supporting the grid and avoiding lack of reliability in the system [15]. For this reason it is interesting to understand if the available hours for grid support are predictable.
Considering the human behaviour, two time periods come to mind: work time period and free time period. During the work time period the vehicles are, usually but not always, driven and the owners could have the possibility to charge their vehicles using public chargers. Since most charging is done at home [4], in this project the possibility of charging the EVs during the working hours, with workplace chargers, is not considered.

3.1.1 EDISON project

During the EDISON - Electric vehicles in a Distributed and Integrated market using Sustainable energy and Open Network - project [58], the driving behaviour of 1600 Danish households were analyzed over a three year period with a fleet of 184 EVs [15].

Table 3.1: Plug in period averages from EDISON project [15].

Parameter	Mean Value	Standard Deviation
Charge period duration	04:00:12	17 [Min]
Plug in period start SOC	49	4 [%]
Plug in period end SOC	100	2 [%]
Plug in period start	19:10:28	39 [Min]
Plug in period end	07:53:32	29 [Min]

Table 3.1 shows the results of the plug-in characteristics considering a charging power rate of 2.3 kW. The average plug-in period start is at 19:00, with 40 minutes of standard deviation.

3.1.2 Driving trips

Table 3.2 compares the characteristics of the daily trips by car in Denmark, Italy and Norway:

Table 3.2: Driving trips characteristics for Denmark [59, 60], Italy [61, 62] and Norway [60, 63].

Parameter	Denmark	Italy	Norway
Average number of trips per person per day	2.9	2.7	3.26
Average driving distance trip	14.6 km	12.2 km	14.5 km
Average driving distance per person per day	40.1 km*	34.3 km	35.6 km
Total travel time per person per day	54.5 min	1 h 29 min	1h 18 min

*The overall average daily driving distance is about 40 km. For weekdays, the average driving distance is 45 km. The average driving distances of Saturday and Sunday are 34 km and 30 km, respectively.

The values in Table 3.2 are similar, even though landscape, weather, culture, societies between the three countries are different. The three countries have an average travel time per day of circa 1 hour and an average distance of 34-40 kilometres per person per day. Considering circa 1 kWh consumed every 5 km, an EV that travels 35 km needs 7 kWh of energy to be charged again. With a 3.7 kW and 90% efficiency charger, the EV would need 2 hours for be fully charged.

A medium conventional car is typically fuelled every 500-600 km, whereas a medium-size EV can go circa 150-160 km [64], see Table 2.3. In general, the amount of kilometres that a vehicle can be driven depends on driving behaviour, outdoor temperature, etc.. Due to the battery nature, the EVs are more subjected to these factors than the traditional cars. Nevertheless, being 35-40 km the average driving distance and 150 km the EV maximum travel distance, the medium-size EVs can satisfy the average driving need.

Despite the differences between the countries, the rest of the chapter aims to create a model to design EV charging patterns. The model is based on Danish travel data, but knowing the travel data of other countries, the basic idea would be the same.

3.1.3 Charging pattern example

The state-of-charge (SOC) represents the percentage of charge of the battery. It mainly depends on the kilometres driven by the EV between the plug-out time and the plug-in time. The EVs are often considered with a simplified charging pattern, which over-estimates the real needed energy to re-charge the battery.
Previous models assume case scenarios where all EVs have SOC of 25% at the same plug-in time (18:00) [7, 12], but this is a very strong assumption. One of the previous model considers the characteristics of the Peugeot iOn with a 16 kWh Lithium-ion battery. The SOC at the end of the day is 25% of the battery capacity, meaning that the EVs are

driven circa 80 km/day [12], but the average daily distance driven per car in Denmark is approx. 40 km/day and 34 km/day in Bornholm (read Section 3.2). Thus a simple and straightforward example of EV penetration in a LV distribution grid is here presented applying a similar approach of the previous model but with 34 km/day.
Considering a 400 kVA transformer and 110 households (similar to the study cases that will be analyzed in Chapter 4), EVs driven 34 km/day, plug-in time at 17:00, rated power of the chargers of 3.7 kW, the charging time is calculated to be approx. 2 hours. In this view Figure 3.1 illustrates the active power profile for one day long and different EV penetration levels: 25%, 50%, 75%, 100%. 100% penetration means that each household has an EV, and in total there are 110 EVs. Since the reactive power is considered zero for all the EVs, when the maximum active power is approx. 400 kW, the transformer is overloaded. Congestion issues would be present in the described scenario with 100% EV penetration, without even considering the household consumption and grid losses.

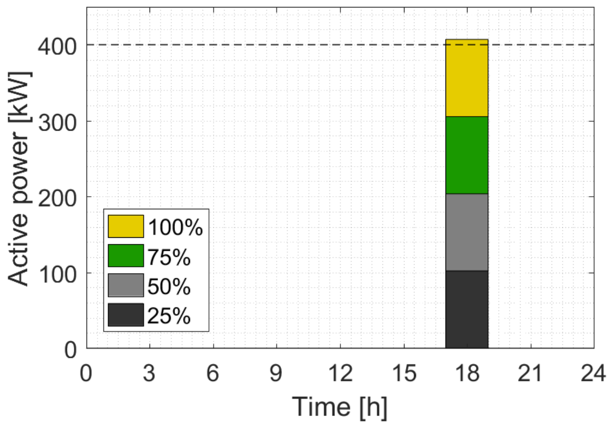


Figure 3.1: One day period, 110 EVs consumption with driven distance 34 km/day, plug-in at 17:00, rated power 3.7 kW. Penetration levels: 25%, 50%, 75%, 100%.

The described scenario, as the previous models, is technically unrealistic because of the strong assumptions. Nevertheless, they show that the main impact of high EV penetration on the power system is congestion issue. Therefore, it is interesting to understand which are the effects of the EV penetration in the power system, when more varied and realistic charging patterns are considered.

3.2 Danish National Travel Survey: data analysis

Between 2006 and 2017 the Danish National Travel Survey interviewed circa 140000 inhabitants of Denmark between 10 and 84 years old [59]. The interviewers had to describe their travelling on the day they were interviewed. Afterwards, the interviewers were statistically weighted per categories considering: day (workday, weekend, holiday), person interviewed (age, gender, education, employment), location (city, municipality, region), trip characteristics (type of vehicle, purpose of trip).

1149 interviewers are inhabitants of Bornholm. The results of the small sample are scaled to 39695, total amount of inhabitants of Bornholm counted in January 2017, deriving that 27620 inhabitants have a driver licence and the number of cars is equal to 19740. Even though the interviewers in Bornholm are a small sample of the entire society, the following results shows similarities with the ones from the whole Denmark.

Analyzing the data from the 1149 interviews, the average number of cars per house results to be approx. 1. Moreover, the scaled results for Bornholm can be summarized as follows:

- average number of kilometres per car per year: 12360;
- average number of kilometres per car per day: 33.8;
- average hours of driving per car per year: 224.

The population of Bornholm drives on average 3% of the time during a year, therefore the cars are parked the remaining 97% of the time and potentially they can be grid connected.

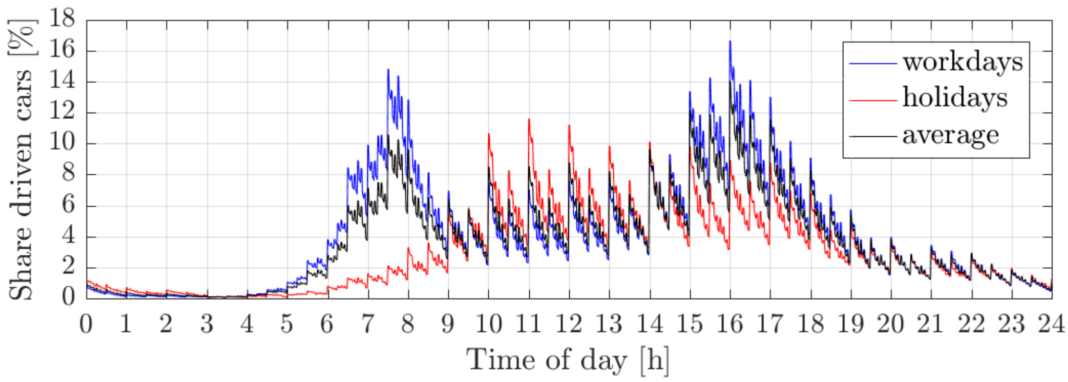


Figure 3.2: Share of driven cars, out of the total amount, in Denmark: workdays, holidays, average.

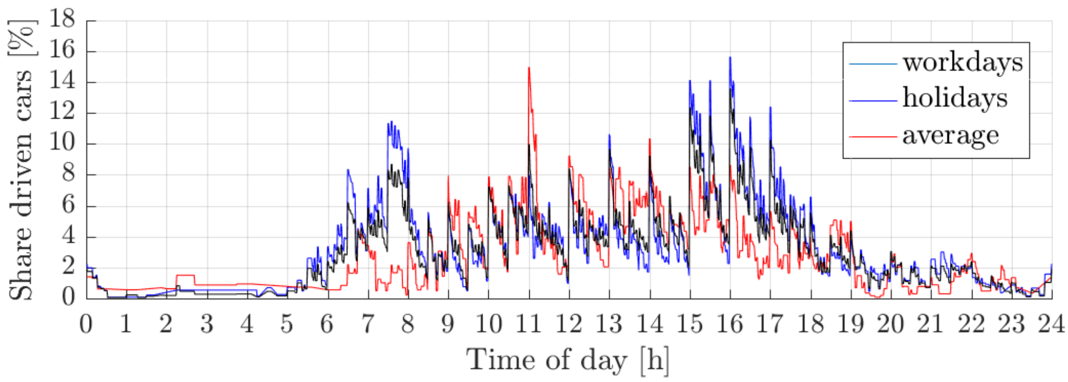


Figure 3.3: Share of driven cars, out of the total amount, in Bornholm: workdays, holidays, average.

Figure 3.2 and 3.3 illustrate the share of driven cars, out of the total amount, during one day period, respectively for Denmark and Bornholm:

- Workdays (weekdays): the blue line represents the cars driven during the workdays. Some peaks are observed around 7-8 and 16-17. In general the Danish population and in specific the Bornholm one, do not use the car very often during the night, from 19 to 7.
- Holidays (weekends): the red line shows the use of car during the weekends. The peaks are distributed between 9 and 17. It is observed that in general the cars are used less in the weekend than during the week.

- Average: the average between weekdays and weekends is the black line, which shows that the final trend is more influenced by the workdays, as the number of workdays is higher.

In Denmark a normal working week is from Monday to Friday, and the office hours are usually between 8/9 and 17. People working in public sectors are used to finish before, at circa 15/16. This working time is also reflected in Figure 3.2 and 3.3.

Figure 3.4 gives information about the distribution of the population per distance driven per day in Bornholm. The average distance driven per day in Bornholm is 34 km, whereas 40 km/day is the average for the whole Denmark. 30 groups with steps of 5 km per group are illustrated, nevertheless the 80% of the population does not drive more than 50 km/day.

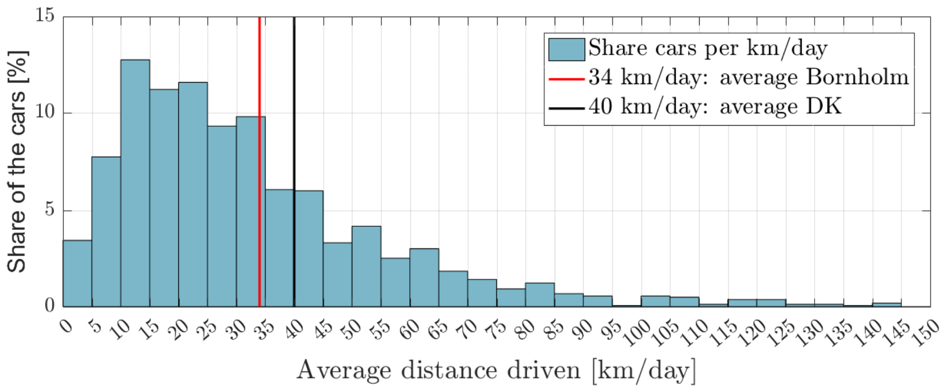


Figure 3.4: Daily average driven distance per share of cars in Bornholm.

3.3 Charging pattern model

In this section a charging pattern model is designed taking into account the users behaviour analyzed in Section 3.2. The model is implemented in Matlab, thanks to its high speed processing of large data sets and to its possibility of interconnection with other programs used for further analysis.

3.3.1 Parameters definition

This section defines the parameters needed for the description of the model.

3.3.1.1 Average distance driven per number of cars: group

The initial idea is to split the vehicles into 10 groups with different travelled distance per day. In figure 3.4, the owners of a car living in Bornholm are divided into 30 groups depending on the driven km/day. In this model the 30 groups are clustered into 10 groups, as shown in Figure 3.5. In Figure 3.4, from 0 to 10 km there are two groups, 0-5 km and 5-10 km, in the new configuration the two groups are summed up into one (G1), as in Figure 3.5. Same procedure is applied to the following groups.

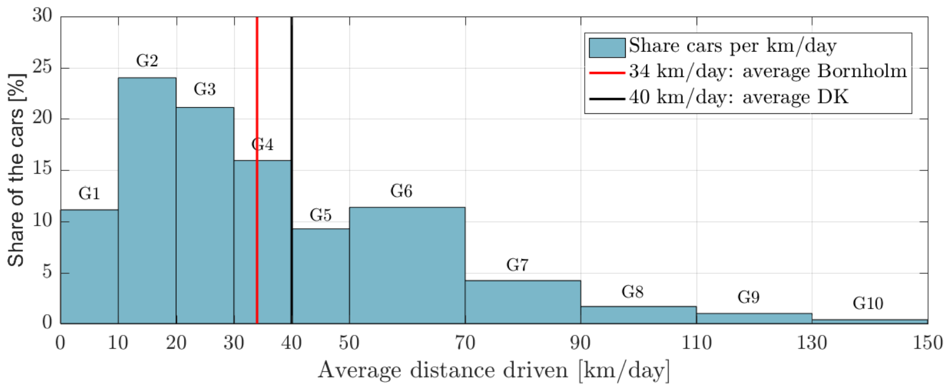


Figure 3.5: Daily average driven distance per share of cars in Bornholm clustered into 10 groups.

Clustering the 30 groups into 10 groups is an important simplification when the considered fleet of EVs is in the hundreds. If 30 groups are considered, few EVs per group would be present and it would be difficult to observe differences between them. On the contrary, if the EVs fleet is in the thousands, the model can be built with 30 groups to observe more variety between the groups. With 30 groups the procedure would be the same described below for the 10 groups, but with different steps of km.
The 10 groups are characterized as follows:

- Groups 1-5: each group contains the cars driven in a certain range of kilometres with steps of 10 km:

  G1: driven distance x: $0 < x \leq 10$ km;
  G2: driven distance x: $10 < x \leq 20$ km;
  G3: driven distance x: $20 < x \leq 30$ km;
  G4: driven distance x: $30 < x \leq 40$ km;
  G5: driven distance x: $40 < x \leq 50$ km;

- Groups 6-10: each group contains the cars driven in a certain range of kilometres with steps of 20 km:

  G6: driven distance x: $50 < x \leq 70$ km;
  G7: driven distance x: $70 < x \leq 90$ km;
  G8: driven distance x: $90 < x \leq 110$ km;
  G9: driven distance x: $110 < x \leq 130$ km;
  G10: driven distance x: $130 < x \leq 150$ km;

The difference between the steps, 10 and 20 km, is reasonable considering that 80% of the vehicles drive less than 50 km/day, as observed in Figure 3.4.
The group number of a vehicle does never change during the simulation and the share of cars per each group can be seen in Figure 3.5.

3.3.1.2 Accumulated kilometres: class

The classes are defined from 1 to 10 and they represent the kilometres accumulated by the vehicle at the end of the day. The class number of a vehicle can be equal or higher than the group number. It can never be lower, since the accumulated km by a vehicle after one or more days can never be lower than the driven kilometres in a day.
The classes are characterized as in Table 3.3.

Table 3.3: Class characterization.

Class number	accumulated km	Class number	accumulated km
1	$0 < x \leq 10$	6	$50 < x \leq 70$
2	$10 < x \leq 20$	7	$70 < x \leq 90$
3	$20 < x \leq 30$	8	$90 < x \leq 110$
4	$30 < x \leq 40$	9	$110 < x \leq 130$
5	$40 < x \leq 50$	10	$130 < x \leq 150$

3.3.1.3 SOC evaluation

The SOC is used in this model to determine the amount of hours that the EVs need to charge, also called charge or charging time. To determine the SOC of the EV at the plug-in time, the maximum kilometres of each class is considered. This may seem an overestimation of the SOC, since not all the EVs of a group drive the maximum number of km of their group. Nevertheless, the SOC depends on the driven km/day, but also on driving behaviour, outside temperature etc., therefore the approximation includes the worst case scenario. The SOC is defined as the remaining capacity of the battery and it can be evaluated in per unit (p.u.), as ratio between the capacity of the battery at time t ($Q(t)$) and the nominal capacity (Q_n), see equation 3.1:

$$SOC(t) = \frac{Q(t)}{Q_n} \tag{3.1}$$

$Q(t)$ is influenced by the operating conditions, such as load current and temperature. Q_n is given by the manufacturer and it represents the maximum amount of charge that can be stored in the battery (40 kWh for the considered Nissan LEAF). $Q(t)$ is determined considering the average range distance equal to 200 km (d_{max}). In accordance with the average energy consumption of 0.214 kWh/km estimated for a Nissan LEAF 30 kWh in [55], the ratio between 40 kWh and 200 km is 0.2 kWh/km. Therefore the average range distance is chosen of 200 km, even though lower than the 240 km (150 miles) from EPA shown in Table 2.3.
The difference between Q_n and $Q(t)$ is the used capacity at time t ($Q_u(t)$). In this analysis SOC and used capacity are calculated only once per day, when the car has travelled its expected distance (defined by the group number) and it is not driven anymore. For this reason time t is from now named day d. The used capacity at day d (Q_u(d)) for the EVs of each group is evaluated with equation 3.2.
The EVs of each group are driven and if they are not charged they accumulate kilometres. If a car did not charge on day '$d-1$', the used capacity on day d ($Q_u(d)$) is higher:

$$Q_u(d) = km_{driven}(d) * 0.2\frac{kWh}{km} + Q_u(d-1) \tag{3.2}$$

$km_{driven}(d)$ is the distance driven on day d, 0.2 is the consumed energy per km. Knowing the used capacity on day d and the battery capacity, the SOC is determined with equation 3.1. The group characteristics are shown in Table 3.4.

Table 3.4: Groups of EVs characterized by driven km/day and SOC at the end of the drive, given initial $SOC = 1$.

Group	Distance x [km/day]	SOC
G1	$0 < x \leq 10$	0.95
G2	$10 < x \leq 20$	0.90
G3	$20 < x \leq 30$	0.85
G4	$30 < x \leq 40$	0.80
G5	$40 < x \leq 50$	0.75
G6	$50 < x \leq 70$	0.65
G7	$70 < x \leq 90$	0.55
G8	$90 < x \leq 110$	0.45
G9	$110 < x \leq 130$	0.35
G10	$130 < x \leq 150$	0.25

3.3.1.4 Plug-in rate at home evaluation

A confidential Japanese statistics conducted by Nissan on 10000 Nissan LEAF 24 kWh derived the probability of charging at home of the commuters, based on the SOC of the daily driven distance.
The human behaviour influences the charging pattern of the EVs. For instance, equal driven kilometres but different driving behaviours cause different SOC at the end of the day. Another factor is the range anxiety, which highly influences the decision of the owners to charge the vehicle. Considering an individual user the range anxiety is difficult to predict, because the users tend to charge their vehicles even when it is not necessary [65]. Differently, considering large groups of EVs, as done by Nissan, it is possible to derive a relation between the plug-in rate and the SOC.
The Japanese research analyzed the level of SOC of the EVs battery when the consumers use to recharge their vehicle at home. It showed that the plug-in rate increases with lower SOC at the end of the day, and at the same SOC, the plug-in rate increases with longer trip distance per day.
Figure 3.6 illustrates a re-representation of the Japanese analysis. As in section 3.3.1.1, in Figure 3.6 ten groups with the same subdivision of km/day are represented: six different lines for the first six groups and a single red line for the last four groups. The last four groups have the same behaviour, because the plug-in rate in the Japanese analysis was very close to 1, therefore the author simplified the model considering the value constantly 1, meaning that the EVs of these groups charge every day. Furthermore, the line "plug-in limit" represents the relation between the accumulated kilometres and SOC.

Starting from the right y-axis, knowing the driven km/day it is possible to determine the SOC of the EVs at the plug-in time with the "plug-in limit" line. Afterwards, for each group of EVs, using the SOC and the left y-axis, the plug-in rate of cars is determined following the respective line of driven km/day of the group.
As aforementioned, G1-G5 have steps of 10 km and G6-G10 have steps of 20 km. Another explanation for this hypothesis is shown in Figure 3.6: lower is the SOC at the end of the day, higher is the plug-in rate. This means that, when driving 90 km or 130 km, the human decision of charging or not is the same: due to the range anxiety, the owner would

charge in both cases. With the Nissan LEAF 24 kWh considered in the Japanese study, consumers that drive above 70 km/day charge their vehicle every day, owing to the range anxiety factor. In this thesis the Nissan LEAF 40 kWh is considered. Nevertheless, due to lack of data about EVs with similar capacities, as conservative estimate it is assumed that the EVs charge when they are driven more than 70 km/day (>70). With 70 km the SOC is 0.65 p.u., as shown in Figure 3.6. EVs of G1-G6 drive less than 70 km/day, but they are forced to charge when they accumulate more than 70 km. Their plug-in rate curves are variable from $SOC = 0.65$ p.u. to $SOC = 1$ p.u., when SOC is lower than 0.65 p.u. all the EVs of the groups are charged. EVs of G7-G10 are instead charged every evening, therefore the plug-in rate is constantly 1.

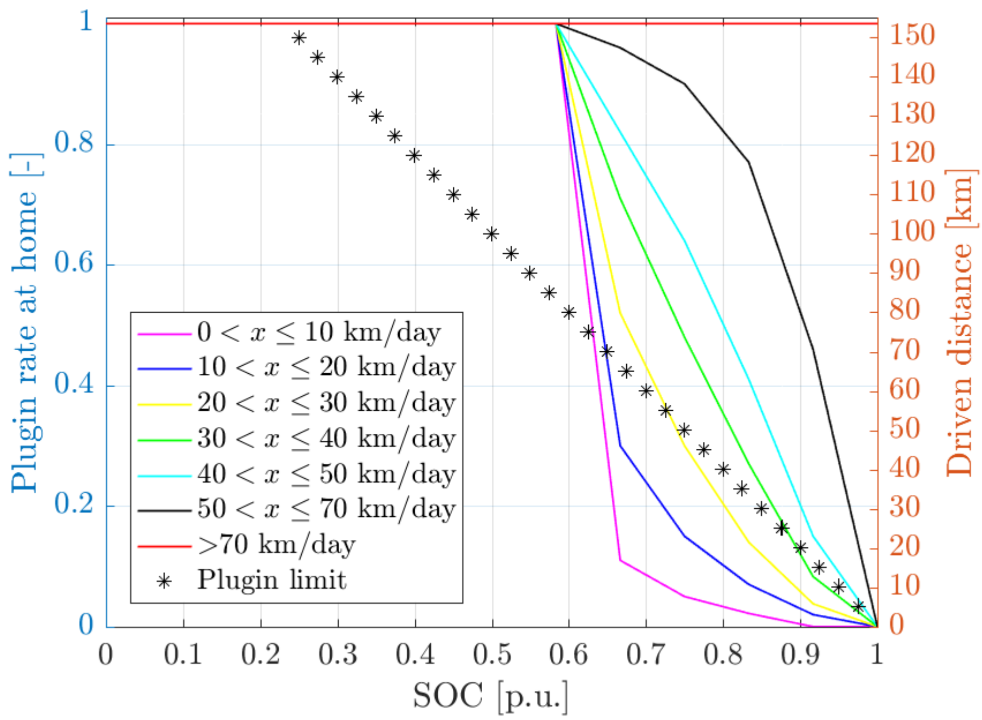


Figure 3.6: Plug-in rate - SOC relation for the 10 defined groups.

3.3.2 Model description

3.3.2.1 General model overview

The model generates individual charging patterns for the EVs, where the sum of the charging patterns fit the analyzed distribution of Figures 3.5 and 3.6. The input of the model are the numbers of EVs and days that want to be simulated. The EVs are then divided into 10 groups, as shown in Figure 3.5. The groups characterize the EVs with their average driven km per day (group). Using Figure 3.6 the plug-in rate at home of the EVs is determined: a part of the EVs charge and the rest does not charge. The share of charging EVs differs depending on the travelled km per day: higher is the group number, higher is the probability of charging. The no charging share accumulates kilometres. To create more variance between the no charging EVs, the no charging share is split into 2 or 3 subgroups depending on their group number. It is important to remember that the vehicles are always part of the same group (km/day), but they change class (accumulated km end-day). The model takes track of each individual EV and its accumulated km, so the output of the model is characterized by one number and one letter for every considered day: the number indicates how many km are accumulated, the letter says if the EV has to charge ("Y" as yes) or not ("N" as no). Knowing these two information, the charging pattern of each EV can be designed, as it will be detailed in Section 3.3.3.

3.3.2.2 Description of the process

The model is described with a flow chart in Figure 3.7.
The input of the model is the number of EVs and the number of days that want to be simulated. Each EV is characterized by its group number. On day d, the group number of each EV is checked: if the group number is larger than 6 the EV charges, if the group number is lower or equal than 6, the class number is also checked. As for the group number, if the class is larger than 6 the EV charges, if the class is lower or equal than 6 the EV goes on with the loop. At the beginning of the simulation all the EVs are considered fully charged ($SOC = 1$), meaning that on day 1 the class number matches the group number of the EV.

An EV of G1 can have classes 1-6, but it never has classes 7-10, since at 70 km accumulated it is forced to charge. An EV of G2 cannot be part of class 1, because it never accumulates less than 10 km, since it never drives less than 10 km/day. For the same reason of an EV of G1, the EV of G2 cannot be part of classes 7-10. Similar approach is applied to the other groups.

All the EVs that do not have group or class number higher than 6 are clustered into categories (f): all EVs with same group and class on day d. EVs part of the same category f enter in "loop b" of Figure 3.7. Using the curves in Figure 3.6, knowing the group and the class number the rate of charging EVs is determined as the "share of charged EVs" ($\%Y$). The rest EVs do not charge ($\%N$). The share $\%Y$ charges, therefore the SOC at the beginning of day 'd+1' is 1 and the km accumulated are reset to 0. The share $\%N$ does not charge, therefore the accumulated km by those EVs increases with the steps shown in Table 3.5 to create more variety between the groups and to avoid over-estimation of the driven km. To better understand how the accumulated steps are increased, an example with EVs from G1 is analysed. The EVs of G1 are driven 0-10 km every day. The first day, at the plug-in time the plug-in rate is determined by line "$0 < x \leq 10$ km per day" in Figure 3.6: the plug-in rate indicates the share of charging EVs ($\%Y$), the rest is not charging ($\%N$). The $\%N$ share starts the second day with a lower SOC than the $\%Y$ share.
EVs of G1 daily drive from 0 to 10 km, but on day 1 the $\%Y$ share charges with charging time that corresponds to cars driven for 10 km. On day 2 EVs of $\%N$ share are driven other 0-10 km. If they are driven 0-5 km, then the accumulated km is lower than 10 km; if they are driven 5-10 km, then the accumulated km is between 10 and 20 km. In this situation, charging all the EVs as they would have driven 10 or 20 km is excessive, therefore the EVs are split into 2 groups, 50% are assumed as driven 0-5 km and 50% 5-10 km. The first group becomes part of class 1, the second becomes part of class 2. EVs in class 1 accumulate maximum 10 km, whereas EVs in class 2 accumulate maximum 20 km. The following days the procedure is the same. If not charged, the EVs continue to accumulate

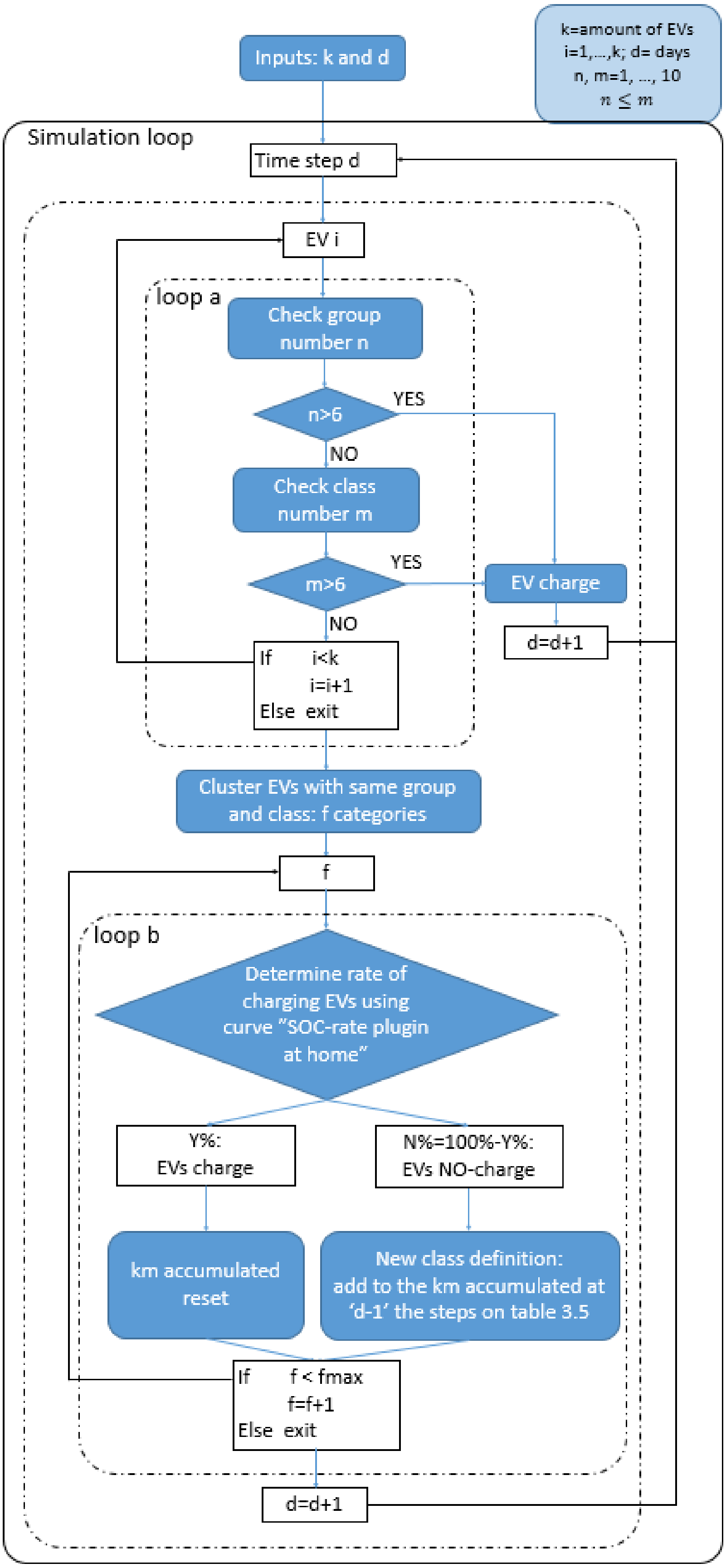


Figure 3.7: Flow chart of the plug-in pattern model.

km and they become part of higher classes, doing steps as shown in Table 3.5. To sum up, the EVs of G1 follow the curve in Figure 3.6, doing steps of 5 or 10 km, being part always of the same group, but changing class which represents the km accumulated.
The same procedure is applied to groups G2-G6: the steps and the percentage of the EVs of each group are shown in Table 3.5.
EVs of groups G7-G10 do never enter in loop b since their group number is larger than 6.

Table 3.5: Steps of accumulated km per day d by EVs that do not charge on day d.

Group	Steps accumulated km per day	Group	Steps accumulated km per day
G1	- 50 % EVs: 0-5 km step - 50 % EVs: 5-10 step km	G4	- 50 % EVs: 30-35 km step - 50 % EVs: 35-40 step km
G2	- 50 % Evs: 10-15 km step - 50 % EVs: 15-20 step km	G5	- 50 % EVs: 40-45 km step - 50 % EVs: 45-50 km step
G3	- 50 % EVs: 20-25 km step - 50 % EVs: 25-30 km step	G6	- 33 % EVs: 50-55 km step - 33 % EVs: 55-65 km step - 33 % EVs: 65-70 km step

When all the categories f are entered in loop b, day d is completed and the simulation loop starts again with $d = d + 1$.

3.3.2.3 Model output

The output of the model is characterized by a number and a letter for each EV and day:

- the number represents the class of the EV at the end of the day, saying the number of accumulated km;
- the letter says if the EV is charging or not: "Y" if charging, "N" if not.

Reconsidering the example in the previous section, at the end of day 1, EVs of G1 have the same class number, because there are no accumulated km from previous days (at the beginning of the simulation all EVs have $SOC = 1$), therefore they are all part of the same category f. During loop b the EVs of this category are split in 2 shares: $\%Y$ are the EVs charging the first evening (1Y), $\%N$ are the EVs not charging the first evening, with accumulated km $0 < x \leq 10$ (1N). See Figure 3.8 for graphical representation. At the end of day 2, the two shares become:

- 1Y is split into 2 other shares: 1Y, 1N. As for day 1, the share of EVs 1Y is determined using Figure 3.6, the rest is not charged 1N.
- 1N is split into 3 shares: EVs that charge (1Y); EVs that do not charge and have accumulated maximum 10 km during the 2 days (1N); EVs that do not charge and have accumulated from 10 to 20 km (2N).

At the end of day 2 there are 5 shares of EVs of G1, but some of them have the same characteristics (number and letter). Thus the EVs with same characteristics are summed up into three shares: 1Y, 1N, 2N. The procedure is the same in the following days, but with creation of more shares, since the accumulated km increase when the EVs are not charged.

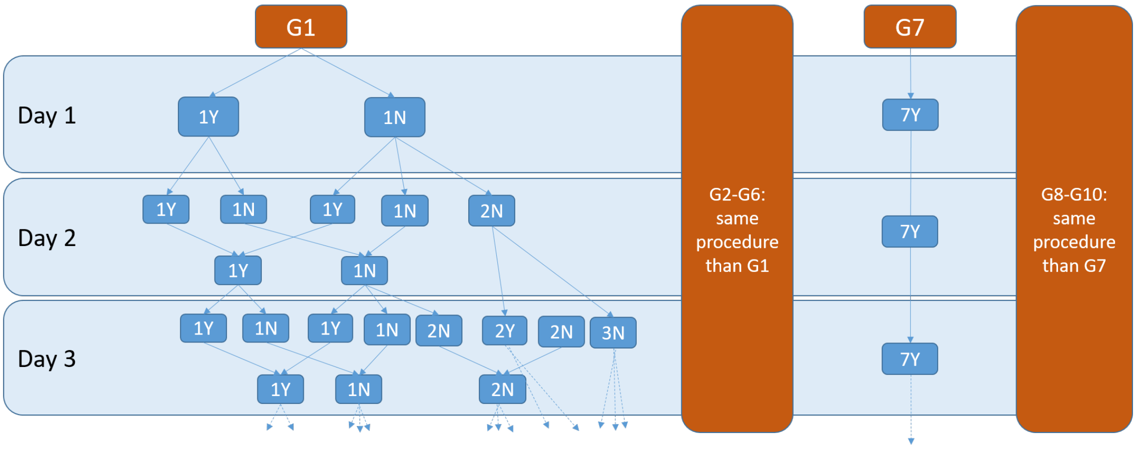


Figure 3.8: Example of share subdivision of EVs.

When an EV is charged, the number of km accumulated is reset and the following day the count starts again from zero for the individual EV. Therefore, the EV is grouped with the EVs with the same class characteristics to evaluate the plug-in rate using the curves in Figure 3.6.

The same procedure is applied to groups G2-G5 using the kilometres distribution of Table 3.5 to determine the new class of the EVs. EVs of groups 2, 3, 4 and 5, if not charged on day 1, they are split into two shares: EVs of G2 do steps of 10-15 or 15-20 km, becoming part of classes 3 and 4; EVs of G3 do steps of 20-25 or 25-30 km, becoming part of classes 5 and 6; EVs of G4 do steps of 30-35 or 35-40 km, becoming part of classes 5 and 7; EVs of G5 do steps of 40-45 or 45-50 km, becoming part of classes 7 and 8. G6 is slightly different from the previous ones, due to the fact that the EVs of this group can drive from 50 to 70 km per day (gap of 20 km). When the EVs are not charged, they are divided into 3 classes: 8, 9, 10, each one with 33% EVs, see Table 3.5. EVs of G6 cannot accumulate kilometres for more than 2 days in a row, since the classes 8-10 represent an amount of accumulated kilometres larger than 70 km, meaning that the second day they need to charge anyway. The difference between these three classes is given by the charging time as it will be explained in Section 3.3.3.
Finally, EVs of G7-G10 are driven more than 70 km per day, concluding that these EVs charge every evening. The difference between the four groups is given as well by the charging time.

3.3.3 Charging time

The described model defines the plug-in charging behaviour of the EVs. In this section the charging patterns, as charging time needed by the EVs is analyzed.

For simplicity the model considers the weekdays profile without distinctions between weekdays and weekends. Given the human behaviour analyzed in Section 3.2, it is realistic to assume that in Denmark, commuters leave their home around 7-8 in the morning and go back home from 16 to 19. Therefore, the EV plug-in times are assumed to be uniformly distributed from 16 to 19, splitting the EVs in 4 sets of 25% EVs at 16, 17, 18, 19. Comparing with the EDISON project results (Table 3.1), where the EVs were plugged in at 19 pm with 40 minutes of standard deviation, this hypothesis is significantly more distributed in time.

In this thesis, the charging patterns are considered as one single session: each EV charges once per day. At low power the Nissan LEAF 40 kWh can charge with constant power, from the plug-in time to the plug-out (almost $SOC = 1$), even when the SOC at the plug-in time is circa 1. This is possible thanks to the battery management system of the Nissan LEAF, that has energy consumption almost constant, differently for example from the Peugeot iOn that changes its consumption over time [66].

Each EV needs a different charging time depending on the accumulated km. The charging time on day d (T(d)) of an EV is calculated using equation 3.3:

$$T(d) = \frac{Q_u(d)}{P_{charger} * \eta} \tag{3.3}$$

with $Q_u(d)$ the required energy at day d, $P_{charger}$ the rated power of the charger and η the efficiency of the charger.
The rated power is the power consumed from the grid: it is 3.7 kW with single-phase chargers (Ch-1ph) and 11.1 kW with three-phase chargers (Ch-3ph). When the EV is not charging or plugged-in but completely charged, the absorbed power is equal to zero.
It is important to observe that 3.7 kW or 11.1 kW are the values of consumed power from the grid. The charger efficiency is circa 90% [66], therefore the battery receives a power equal to the 90% of the absorbed charging power from the grid:

$$P_{Ch-1ph} = 3.7 * 0.9 = 3.33kW \qquad P_{Ch-3ph} = 11.1 * 0.9 = 9.99kW$$

with Ch-1ph and Ch-3ph chargers, respectively.

Table 3.6: Comparison of needed and implemented EVs charging time considering Ch-1ph and Ch-3ph chargers.

	Class	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Ch-1ph	*Charge time [min]*	36	72	108	144	180	252	324	396	468	540
	Implemented charge time [min]	35	70	110	145	180	250	325	395	470	540
Ch-3ph	*Charge time [min]*	12	24	36	48	60	84	108	132	156	180
	Implemented charge time [min]	10	25	35	50	60	85	110	130	155	180

The charging patterns are designed in this thesis with time step of 5 minutes. For this reason the charging time, as calculated with equation 3.3, is rounded to the closer value multiple of 5, see Table 3.6. The plug-in model code is run for two weeks (14 days). Since all EVs are fully charged ($SOC = 1$) at the beginning of the simulation, the first week is disregarded and the analyzed scenario starts from week 2. This is necessary to get a realistic SOC distribution on day 1, as the EVs are expected to have differentiated SOC.

3.3.4 Applied example: 20 electric vehicles

The model is applied to an example with 20 EVs and 14 days of simulation. The EVs are split into the 10 groups, but due to the low amount of EVs, only 7 groups are actually created, see Table 3.5.

Table 3.7: Plug-in model output per group and per day: example with 20 EVs.

		Week 1							Week 2						
	EV	1	2	3	4	5	6	7	*1*	*2*	*3*	*4*	*5*	*6*	*7*
G1	***1***	1N	1N	2N	3N	4N	5N	6N	**7Y**	**1N**	**1N**	**2N**	**3N**	**4N**	**5N**
	2	1N	2N	3N	4N	5N	6N	7Y	**1N**	**1N**	**2N**	**3N**	**4N**	**5N**	**6N**
G2	***3***	2N	3N	5N	6Y	1N	2N	4N	**5N**	**6Y**	**1N**	**2N**	**4N**	**5N**	**6Y**
	4	2N	4N	4N	5N	6N	7Y	1N	**3N**	**5N**	**6N**	**7Y**	**1N**	**3N**	**5N**
	5	3N	4N	5N	6N	7Y	1N	3N	**5N**	**6N**	**7Y**	**1N**	**3N**	**5N**	**6N**
	6	3N	5N	6Y	1N	3N	5N	6N	**7Y**	**1N**	**3N**	**5N**	**6N**	**7Y**	**1N**
	7	3N	5N	6N	7Y	1N	3N	5N	**6N**	**7Y**	**1N**	**3N**	**5N**	**6N**	**7Y**
G3	***8***	3Y	5N	6Y	2N	4N	6N	7Y	**2N**	**4N**	**6N**	**7Y**	**2N**	**4N**	**6N**
	9	4N	5Y	2N	4N	6N	7Y	2N	**4N**	**6N**	**7Y**	**2N**	**4N**	**6N**	**7Y**
	10	4N	6N	7Y	2N	5N	6Y	2N	**5N**	**6Y**	**2N**	**5N**	**6Y**	**2N**	**5N**
	11	5N	6Y	2N	5N	6Y	2N	5N	**6Y**	**2N**	**5N**	**6Y**	**2N**	**5N**	**6Y**
	12	5N	6N	7Y	2N	5N	6N	7Y	**2N**	**5N**	**6Y**	**2N**	**5N**	**6Y**	**2N**
G4	***13***	4Y	6N	7Y	3N	6N	7Y	3N	**6N**	**7Y**	**3N**	**6N**	**7Y**	**3N**	**6N**
	14	5N	6Y	4Y	6N	7Y	4Y	6N	**7Y**	**4Y**	**6N**	**7Y**	**4Y**	**6N**	**7Y**
	15	6N	7Y	3N	6N	7Y	3N	6N	**7Y**	**3N**	**6N**	**7Y**	**3N**	**6N**	**7Y**
G5	***16***	5Y	5Y	5Y	5Y	5Y	5Y	5Y	**5Y**	**5Y**	**5Y**	**5Y**	**5Y**	**5Y**	**5Y**
	17	8N	8Y	5Y	8N	8Y	5Y	8N	**8Y**	**5Y**	**8N**	**8Y**	**5Y**	**8N**	**8Y**
G6	***18***	6Y	6Y	6Y	6Y	6Y	6Y	6Y	**6Y**	**6Y**	**6Y**	**6Y**	**6Y**	**6Y**	**6Y**
	19	6Y	6Y	6Y	6Y	6Y	6Y	6Y	**6Y**	**6Y**	**6Y**	**6Y**	**6Y**	**6Y**	**6Y**
G7	**20**	7Y	7Y	7Y	7Y	7Y	7Y	7Y	**7Y**	**7Y**	**7Y**	**7Y**	**7Y**	**7Y**	**7Y**

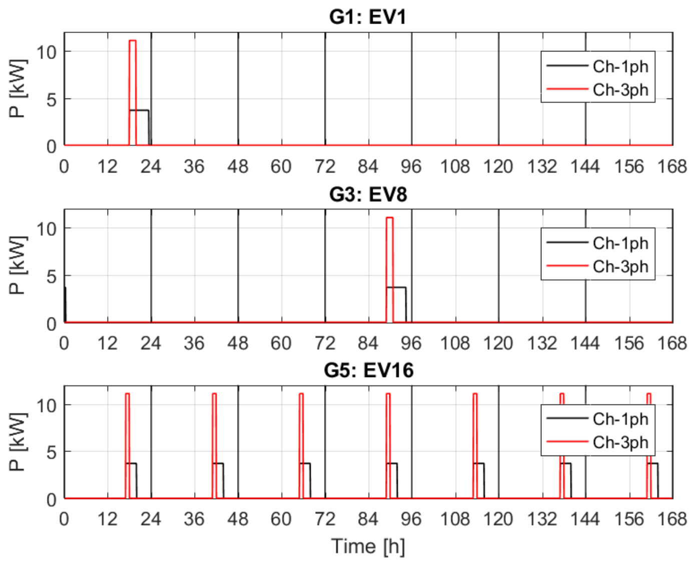


Figure 3.9: Charging patterns of EV1, EV8, EV16 seen in Table 3.7 with Ch-1ph and Ch-3ph chargers.

Table 3.7 shows the results for the two weeks of the 20 EVs. Every day each EV has one number and one letter that represent its behaviour at the end of the day, as described in Section 3.3.2.3: the number is the class, the letter says if the EV is charging (Y) or not (N). The table shows the triviality of the first week (seven days), indeed many EVs are not charging on the first days. Figure 3.9 shows a graphical example of the charging patterns of vehicles EV1 (G1), EV8 (G3) and EV16 (G5), highlighted in Table 3.7 with the green numbers. The black lines are the Ch-1ph charging, the red are the Ch-3ph charging.
EV1 (EV number 1, group 1 - G1) charges on day 1 week 2: its code is 7Y → class 7 and charging yes (Y). The class is 7, because the accumulated km are between 70 and 90, therefore the charging time is of 325 minutes with Ch-1ph and 110 with Ch-3ph, see Table

3.6. The following 6 days EV1 does not charge, so the power is constantly equal to 0 kW. In the same way the other charging patterns are derived. Higher is the group number of the EV, higher is the amount of times that the EV charges per week. The EV charges the same amount of times with Ch-1ph and Ch-3ph, but with the first, the charge time is three times than the second.

3.4 Summary

In this chapter the model to design the EV charging patterns has been defined. The strong assumptions of previous models [7, 12], where all the EVs were plugged-in at the same time and had the same energy consumption were removed in the model proposed in this thesis, to create more realistic charging patterns, with different energy consumptions and plug-in times. Even though the model was based on Danish data, it provides an approach and base for future studies on the topic. Based on the Danish driving data and statistics, the model generates individual charging patterns for the EVs, simulating the charging pattern distribution of a group of vehicles from the Japanese study. The main input of the model is the number of EVs, these are firstly divided into groups with different average distance driven per day and afterwards they are used to generate the charging patterns. Thanks to the confidential Japanese statistics, it was observed that EV users plug-in their vehicle more times per week with higher average driven km/day. For the defined amount of days, the model determines if the EV has to charge and which is its SOC at the end of the day. Based on the Danish national travel survey, the plug-in charging time of the EVs was divided into four sets, 25% EVs per each plug-in time: 16, 17, 18, 19. Finally, an example with 20 EVs showed the variety of the charging patterns designed with the described model.

The model will be used in the thesis to simulate the impact of EV penetrations in two grids of Bornholm, which will be presented in Chapter 4.

4 Grids topology and consumption data analysis

Starting from an overview of the electricity system of Bornholm, this chapter moves on the analysis of the grid configuration of the two Danish study cases: one in Tejn and one in Rønne. Afterwards the household consumption data of two winter weeks are compared. Finally the eight ±10 kW ENEL DC chargers present in Rønne are described and the active power consumption is determined.

4.1 Bornholm: electricity system overview

Bornholm is a small Danish island of 588.5 km^2 located in the south of Sweden, see figure 4.1.

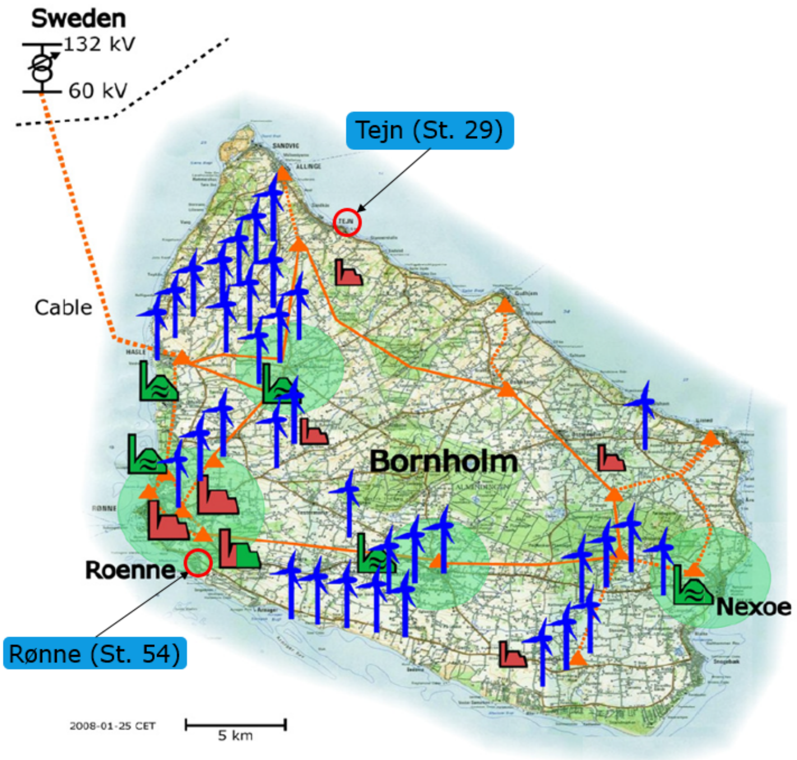


Figure 4.1: The island of Bornholm with major generation units and 60 kV grid [9]. The geographical location of the analyzed grids in this thesis are highlighted: Tejn and Rønne.

In Bornholm Bornholms Energi & Forsyning (BEOF) is the DSO that supplies electricity to more than 28000 customers. Bornholm corresponds to approx. 1% of the total Danish population and electricity demand. The electric power system, technically and economically, is part of the Nordic system. The electricity grid is normally connected to the mainland (Sweden) through a sea AC cable (60 kV) with a transfer capacity equal to 50 MVA, 43.5 km offshore. Today the wind power penetration is more than 30% of the load and the complete generation can be summarized as follows [9]:

- 16 MW biomass combined heat and power (CHP), steam turbine (can be boosted to approx. 24/36 MW if running on coal/oil), with droop control (2%) and voltage control Ramping rate 2MW/10 min
- 2 biogas CHP of 1 MW each, gas turbine. No droop control
- 37 MW wind (24 machines <100 kW; 16 machines between 100 and 1000 kW; 17 machines > 1000 kW)
- 8 MW PV plus 15 MW added in May 2018
- 58 MW reserve (used during islanded operation): 25 MW of oil steam turbine, 18 MW of old diesel (1967-1972) and 15 MW of new diesel (2007).

To improve power quality and security of supply, the island is connected to the Nordic power system, even thought thanks to the 127 MW of total generation capacity the system can be operated in islanding mode [9, 67].

The possibility to run the Bornholm power system in isolated mode, makes the island an interesting test for different activities: flexibility of old generating plants, delivery of ASs, interconnection of power systems, demand side contribution, predictability of the volatile sources. In 2007 some islanding operations were conducted, showing the importance of tactical manoeuvres to prepare the system. Firstly the power had to be adjusted through the sea cable, secondly different wind turbines were shut down and some reserves were started. Even though in islanding mode the share of wind production was lower than the normal situation, the analysis revealed a decrease on the frequency controllability.
Another islanding operation was made in Autumn 2017, when the cable had to be de-energized for maintenance from the 18 September to the end of the month. Wind turbines were limited and all renewables non-controllable were disconnected, moreover the electric consumption was relatively low (peak of 30 MW), due to the warm season period. In these conditions no frequency fluctuations were observed.
This showed that, if the correct number of reserve is activated, the frequency is not deviating a lot, thanks to the large generation capacity with droop control integration present in Bornholm.

As part of DK2, in Bornholm the TSO, Energinet, has to provide the same ASs as in the rest of the DK2, supplying the following reserves: frequency-controlled disturbance reserve, frequency-controlled normal operation reserve, manual reserves, short-circuit power, reactive reserves and voltage control [68].

To conclude Bornholm is used as an experimental facility to reach the goal of 100% renewable power generation. Several researches are active in the field to deal with flexible demand and power market, island operation, wind power integration, EV integration [69]. As part of the last topic, this thesis analyzes different EV penetration levels considering two grids of the island.

4.2 Topology of the simulated distribution grids

Considering the LV grid, it is important to specify how customers are connected to the Bornholm power system. The dominant grid-household connection in Denmark is the three-phase (3-phase) with neutral cable. Due to this type of connection, the DSOs cannot decide where the customer or the technician connect the appliances in the building. This leads to high possibility of load imbalance, having for example 50% of the power flowing in one of the three phases.
Figure 4.2 shows the boundaries of the power lines and main circuits for different kinds of house in a LV distribution grid. Starting from the bottom of the figure, BEOF is responsible for maintenance of the power system up to the "Grænseflade" line, interface between DSO and consumers. Above the Grænseflade line, the consumer becomes responsible for the components that interconnect the interface with the building, including costs and maintenance of the connection cable.

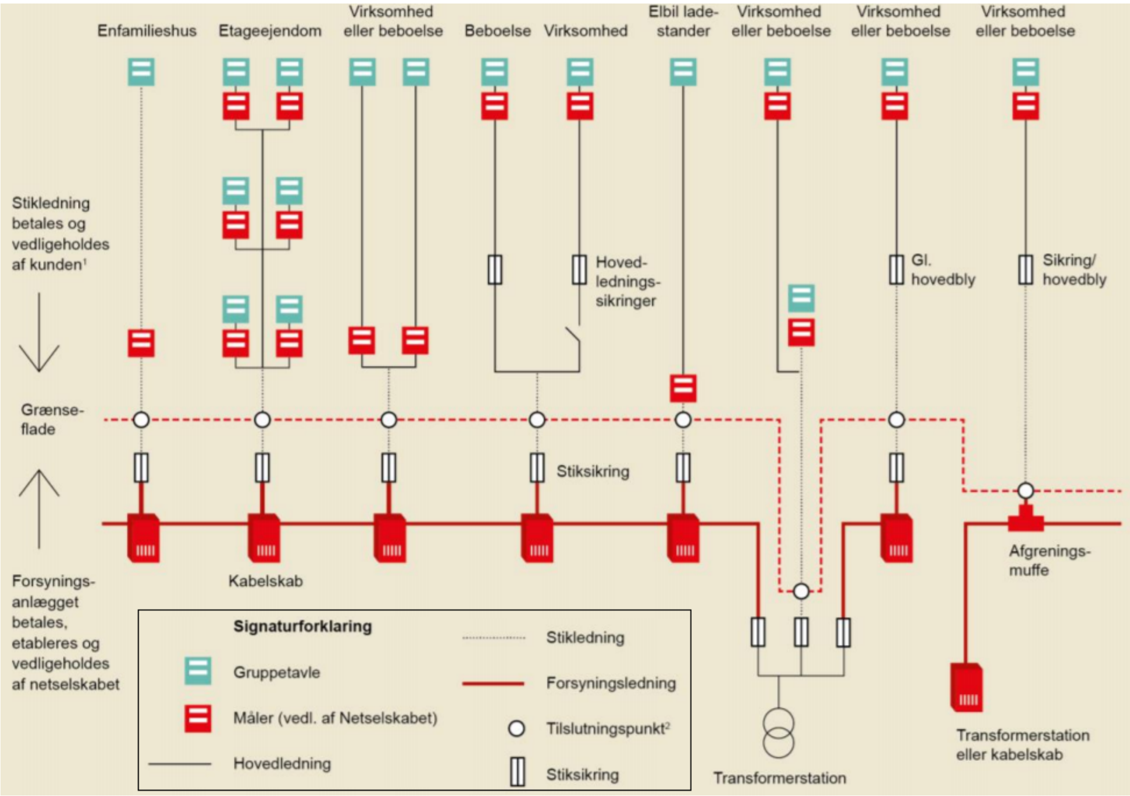


Figure 4.2: Power lines and main circuits (Stikledninger og hovedstrømskredse) [10].

The grid layout of the two analyzed study cases, Tejn and Rønne, are provided by BEOF.

4.2.1 Tejn: Station 29

Tejn is a harbour town on the north-eastern coast of Bornholm. In this project only station 29 (St. 29), supplying a part of the town, is considered. The author will refer to this grid using the names "Tejn" or "St.29". The analyzed network is a radially run, semi-urban LV grid (Unom=400 V), wired to the MV external grid (Unom=10 kV), through a 10/0.4 kV 400 kVA distribution transformer and supplied by under-ground cables with technical characteristics shown in Table 4.1.

Table 4.1: Cable characteristics.

Type	V [kV]	I [kA]	R' [Ω/km]	X' [Ω/km]	R0 [Ω/km]	X0 [Ω/km]
4x95 Al	0.4	0.235	0.320	0.069	1.280	0.276
4x25 Al-M PEX	0.4	0.100	0.866	0.086	3.462	0.344
4x50 Al-M PEX	0.4	0.155	0.640	0.079	2.57	0.314
4x95 Al-M PEX	0.4	0.235	0.320	0.075	1.280	0.302
4x150 Al-M PEX	0.4	0.335	0.207	0.073	0.829	0.312
4x16 Cu PVIKS	0.4	0.100	1.150	0.089	4.610	0.358
4x70 Cu PVIKS	0.4	0.230	0.269	0.082	1.070	0.329
4x95 Cu PVIKS	0.4	0.300	0.212	0.082	1.070	0.329

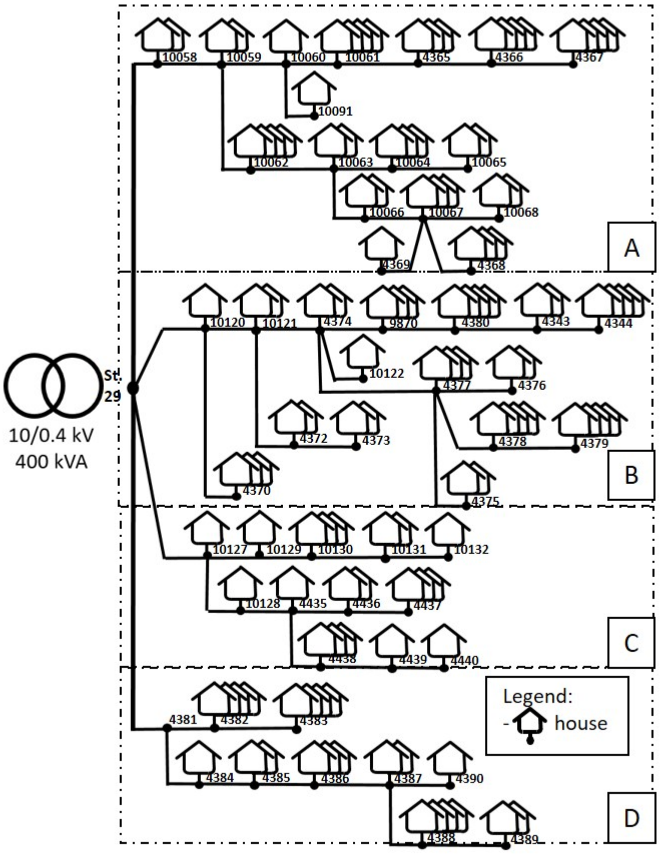


Figure 4.3: Tejn grid layout.

The analyzed network is a radially run, semi-urban LV grid (Unom=400 V), wired to the MV external grid (Unom=10 kV), through a 10/0.4 kV 400 kVA distribution transformer and supplied by under-ground cables with technical characteristics shown in Table 4.1. Considering the method of symmetrical components (read Appendix A.1 for theoretical explanations), R' and X' are the resistances and reactances of the positive and negative sequence of the cables, whereas R0 and X0 are the zero sequence components. V and I are the rated voltage and current (ground), respectively. The three bold types are the cables used at the beginning of the grid to connect station - terminals (the green color are the ones used in Rønne).
Figure 4.3 illustrates the configuration of the grid. From the transformer, the grid is split into four areas through four lines that branch into various cables and terminals, with the consumers distributed among them. Each terminal is named in the figure with a number,

and the houses represented in each terminal specify the amount of houses present in the reality. With an average of 2.4 households per terminal, the 127 households are placed in the four areas as follows:

- area A: 43 households;
- area B: 41 households;
- area C: 20 households;
- area D: 23 households.

In Tejn there are 11 photovoltaic (PV) installations (all around 6 kW), some houses are supplied by district heating and others have electric heating.

4.2.2 Rønne: Station 54

Rønne is the largest town in Bornholm. In this project only station 54 (St. 54), supplying a small part of the city, is considered. The author will refer to this grid using the names "Rønne" or "St. 54". The technical characteristics are very similar to the ones of Tejn. St. 54 is a radially run network, semi-urban LV grid (Unom=400 V), wired to the MV external grid (Unom=10 kV), through a 10/0.4 kV 400 kVA distribution transformer, and supplied by under-ground cables with the technical characteristics shown in Table 4.1. The two green types are the cables used at the beginning of the grid to connect station - terminals.

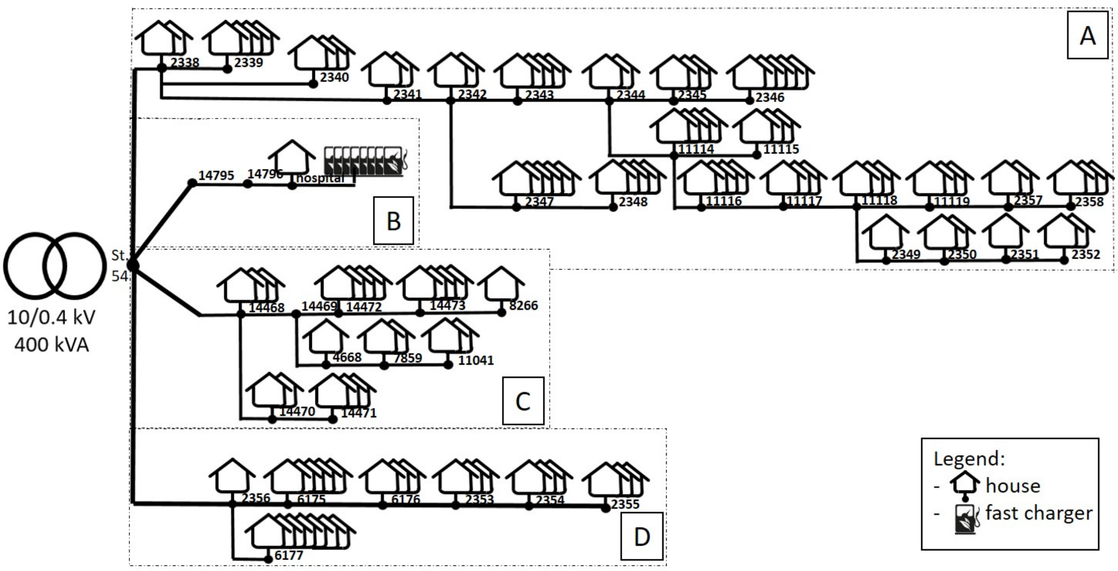


Figure 4.4: Rønne grid layout.

Figure 4.4 shows the grid layout. From the transformer, the grid is then divided in five areas, since one does not have installations/customers connected yet, only four of them are active and shown in Figure 4.4. The four areas are connected to the transformer through four lines that branch into various cables and terminals, with consumers distributed among them.

With an average of 2.9 households per terminal, the 110 households are placed in the four areas as follows:

- area A: 67 households;

- area B: hospital and 8 ±10 kW ENEL DC chargers;
- area C: 22 households;
- area D: 25 households.

Four household meters, in terminals 2338, 2339, 2340 and 11114, are inactive for unknown reasons to the author, therefore their consumption is considered equal to zero and the final number of consumers is 110. In Rønne the district heating is common and there are no PV installations. Moreover, eight ±10 kW ENEL DC chargers (fast chargers) are connected in area B.

To avoid low voltages at the end of the grids, it is common for the DSOs to fix the voltage at the transformer higher than 1 per-unit (p.u.). In this project the voltage at the transformer, both in Tejn and Rønne, is consider equal to 1.025 pu.

4.3 Household consumption

4.3.1 Comparison week 7 and 9

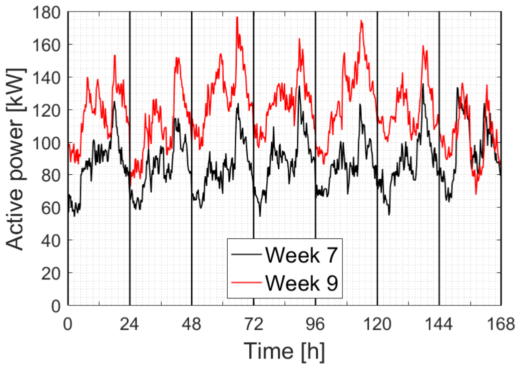
The following analysis is based on the data from the new EU smart meters introduced in Section 2.3.1. The smart meters measure the electricity consumption and provide to the final customers information on the actual time of use. The smart meters acquire different kinds of data as sum of the three phases: active/reactive power, voltage, outages etc.. In case of connection problems, the smart meters interpolate the available known data.
The smart meters data were provided to the author by BEOF as sum of the three phases active power consumption with steps of 15 minutes. In the following analysis the data from two winter weeks are compared:

- Week 7: from 12th to 18th February 2018
- Week 9: from 26th February to 4th March 2018.

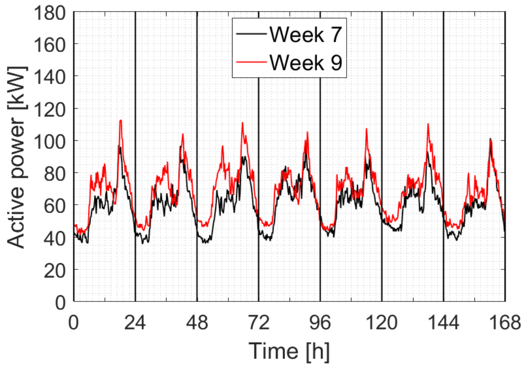
In week 7 the average measured temperature in Denmark was 2 degrees. In week 9, the temperatures were lower, with values of -10/-15 degrees. The average temperature was approx. -6 degrees and the weather was also called "the Siberian cold" [70].

Figure 4.5a and 4.5b show the sum of the household consumptions during weeks 7 and 9, respectively in Tejn and Rønne. In Tejn the total consumption is approx. 20 kW different between the two weeks, whereas in Rønne it is almost the same. This is because in Tejn some households have electric heating, but due to private information, the amount of households with electric heating is unknown to the author. Nevertheless, thanks to some more data provided by the EcoGrid[1] project [71], at least 20 households are known to have electric heating.
Figure 4.6 illustrates the sum of the consumption of these 20 households, showing that the consumption is more than doubled in some days of the colder week 9.

[1]EcoGrid is a project that studies the electricity market with flexible power consumption in private households present in Bornholm. The 1000 households of the project have heat pumps electric radiators and are remotely controlled to optimize their power consumption.



(a) Tejn.



(b) Rønne.

Figure 4.5: Total household consumption, comparison week 7 and 9.

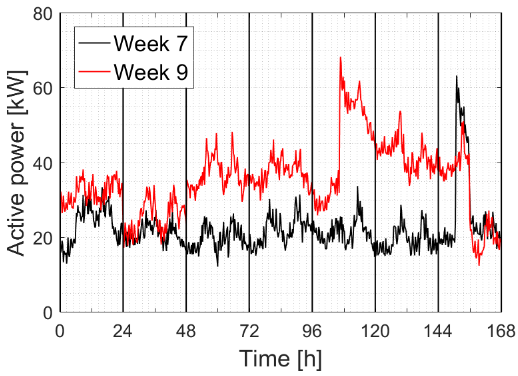


Figure 4.6: Tejn: consumption of 20 households with electric heating, comparison between week 7 and 9.

This comparison is intended to clarify how the dependence on electric heating can heavily weigh on the electrical load. Since the grid has to be dimensioned for the worst case, the domestic consumption data from week 9 are used for the investigations of the grids.

It is worth mentioning that the two analyzed study cases, Tejn and Rønne, represent a typical LV distribution grid in Bornholm. In the island there are 985 MV/LV transformers with an average nominal power of 240 kVA. With a total peak load of 55 MW [9], the average peak consumption of each transformer is circa 56 kW. The ratio between the average peak consumption and the average nominal power is 0.23 (56 kW/230 kVA). Similarly, the ratio in Rønne is 0.28 (110 kW/400 kVA), whereas in Tejn the ratio is 0.38 if considering week 9 (150 kW as average peak), and 0.30 when considering week 7 (120 kW as average peak).

4.3.2 Reactive power

The provided household consumption data do not include the reactive power. To consider the reactive power consumption in the analysis, the values are calculated as in equation 4.1:

$$Q(t) = P(t) * \tan\left(\cos^{-1}\left(\cos\phi_{av}\right)\right) \tag{4.1}$$

with $P(t)$ the known active power at time t.
To determine the reactive power, the power factor ($\cos\phi_{av}$) has to be evaluated considering the EcoGrid data. These data are given as active and reactive power consumption of the 20 households present in Tejn, from the 4th January 2017. The data have 5 minutes steps, therefore the $\cos\phi$ of each household is determined as average of the values of one-day period. The $\cos\phi$ at each time step is evaluated as in equation 4.2:

$$\cos\phi(t) = \frac{P(t)}{\sqrt{P(t)^2 + Q(t)^2}} \tag{4.2}$$

Then the average value for each household is determined. Afterwards the mean of the 20 values of the power factor is evaluated and assumed as $\cos\phi_{av}$ for all the householders of the project. The determined $\cos\phi_{av}$ is 0.966, realistic value if compared with the one regulated by Energinet of 0.95 [72].

The EcoGrid data are provided only for Tejn, therefore the $\cos\phi_{av}$ is assumed equal to 0.966 for the household in Rønne as well.

4.3.3 Phase loading

The purpose of this section is to determine the average loading unbalance on the three phases for the two grids. The average loading will then be set for each load of the feeders during the modelling of the grid in Chapter 5.
This analysis is based on the data from the Smart Grid Unit (SGU) meters, new meters installed by ACES project at the transformer station of the two grids:

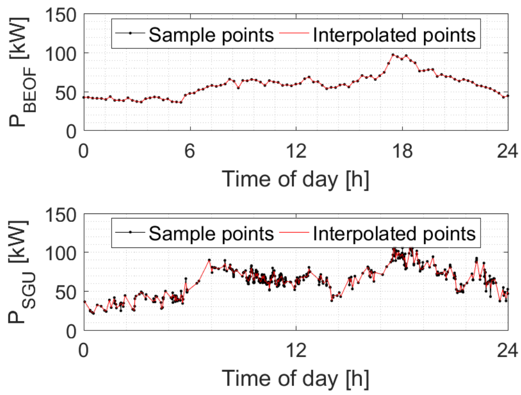
- Tejn: St.29, Kildesgårdsvej 2,Tejn, 3770 Allinge
- Rønne: St. 54, Bellmannsvej 22 and 24, 3700 Rønne.

The SGUs measure current, voltage and power factor per each phase, then they elaborate active and reactive power values. The SGUs keep a table of the current measurements as well as the previously transmitted measurement. Each 2 seconds the SGUs compare these two tables and transmits the measurements that have changed since the last transmission. If, for instance, the current of phase a and b have changed by 0.1 A or more, but the current of phase c has not changed, only the measurements pertaining phase a and b will be transmitted. This means that the SGUs do not log data if the values do not change, causing non-uniformity between the final data.

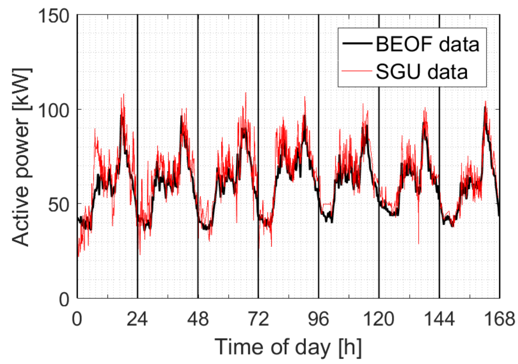
The data analysis is presented in detailed for the study case of Rønne, however the same procedure has been applied to Tejn and the results can be found at the end of the section. Moreover, the analysis is based on data from week 7, since the SGUs data were not provided for week 9. Nevertheless, the goal is to analyze the current distribution on the three phases, which average is expected to be the same for the two weeks.

The total electric load consumption is here the sum of the household consumptions from the smart meters, without the losses in the grid. The household consumption data have steps of 15 minutes as analyzed in Section 4.3.1. Differently, for the reason explained above the SGUs data have discontinuous intervals.

Figure 4.7a compares the data provided for one day: on top the data provided by BEOF and on bottom the data from the SGUs. The red line shows the spline interpolation of the available data, the blue dots highlight the different data availability of the two cases. In Figure 4.7b the active power at the transformer is compared with the sum of the household consumptions. The general trend of the two curves is similar, validating the measurements of the SGUs which have never been analyzed before. Nevertheless it happens that the SGU data are lower than the sum of the household consumptions. This is unrealistic considering that the SGUs data include the losses of the grid, but it is due to two reasons: first the fast chargers (often discharging during the night, when the SGUs data tend to be lower than the household consumption), are not considered in the sum of the household consumption, since their consumption data [2] are unknown and they will be derived in Section 4.4. Second, measurement mistakes can be present if the household smart meters are interrupted, then they display interpolated data for a certain period of time.



(a) One day comparison.



(b) One week comparison.

Figure 4.7: BEOF - SGU data comparison, week 7 Rønne.

Going back to the main point of this section, it is important to determine the current distribution on the three phases to determine if the power system is balanced or unbalanced. In turn, this is necessary for the thesis to model the feeders in a realistic way, avoiding for example overestimation of the voltage magnitude behaviour at the end of the feeders. The currents are measured by the SGUs and they show an unbalanced distribution on the three phases: phase a is more loaded than b and c. A maximum peak of 52% of the total current flowing in phase a is reached. The average loading values are: 37% phase a, 32.5% phase b and 30.4% phase c.

In Tejn a similar unbalanced situation is present, with average values of 37.4% for phase a, 29.7% for phase b and 32.8% for phase c.

The average loading of the three phases will be considered in the grid modelling as 40% in phase a, 30% in phase b and 30% in phase c, approximation that takes into consideration the imbalance of the system with higher loading of phase a.

[2]The 8 10 kW DC chargers have a consumption equally distributed between the three phases, therefore their absence in this section does not influence the phase imbalance.

4.4 Fast charger consumption

In Rønne eight ±10 kW ENEL DC chargers (fast chargers), are connected to the power system as shown in Figure 4.4. The fast chargers and EVs are owned and used by the municipality. The EVs are mainly driven during the day and charged during the night. The EVs can be used by the aggregator between 22:00 and 6:00 for frequency regulation, but at the same time the users are ensured to have the EVs fully charged at 6:00 in the morning.
The meters of the DC chargers were not logging during week 9, therefore no power data are available from this week. It is not possible to consider another week for the consumption data, because the consumption is function of the frequency of the whole system, always different from one week to another. Therefore, to implement the fast chargers into the system the frequency data (f_{mea}) are used. The f_{mea} are provided by BEOF SCADA system with one-minute resolution for week 9. Before presenting the active power consumption during the week, the basic theory behind the frequency regulation is explained.

4.4.1 Theory: frequency regulation

The frequency control is realized via active power management, either on generation or consumption side. The frequency is the measurement of how much a system is (im)balanced, as shown in equation 4.3:

$$P_m - P_e = J\omega\frac{d\omega}{dt} \tag{4.3}$$

where P_m is the produced and P_e the consumed power at system level, J is the system inertia (sum of all rotating masses) and ω is the electric rotational speed of the machines, related to the frequency with equation: $\omega = 2 * \pi f$.
If the generation is larger than the consumption, then the frequency increases. Similarly, if the consumption is larger than the generation then the frequency decreases [33].

4.4.2 Droop control

Considering the European nominal frequency (f_n) of 50 Hz, the frequency variation (Δf) is defined as in equation 4.4:

$$\Delta f = f_{mea} - f_n \tag{4.4}$$

The upper threshold is set to 0.1 Hz, above this Δf the chargers deliver at full power (10 kW). The lower threshold is equal to -0.1 Hz, where the chargers receive at full power. The power (P_{DC}) injected or absorbed by the chargers is calculated as in equation 4.5:

$$P_{DC} = \frac{\Delta f}{0.1} * P_{cap} + P_{offset} \tag{4.5}$$

with P_{cap} the power capacity equal to 9 kW and P_{offset} the fixed power offset of 1 kW at nominal frequency. The efficiency of the charger at nominal power is 90%, but it decreases with frequency regulation. The average loss for the car with frequency regulation is 20%, therefore, due to the efficiency of the chargers, 1 kW offset is used to avoid the full discharge of the battery. The described droop control for one fast charger is graphically shown in Figure 4.8.

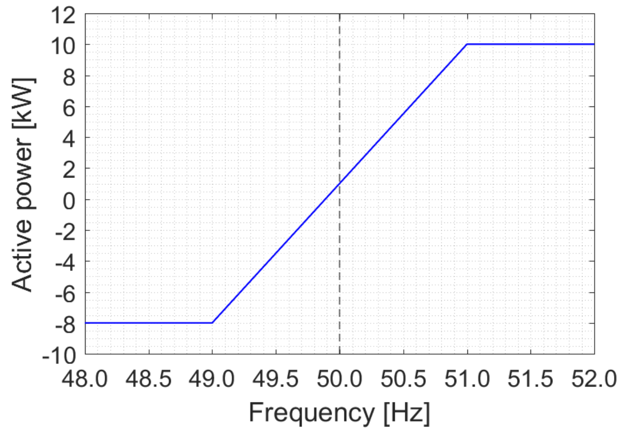


Figure 4.8: Droop control of one fast charger present in Rønne.

4.4.3 Power behaviour modelling

Knowing the frequency of the power system, the active power of the fast chargers can be determined.
Thanks to previous results of a similar analysis in the Frederiksberg municipality (more info can be found in [29]), the active power can be assumed to be composed of three parts:

- from 22:00 to midnight and from midnight to 4:00 the EVs are used for frequency regulation;
- from 4:00 to 6:00 the EVs are charged: each EV is considered to be driven approx. 80 km every day. After the frequency regulation and before 6:00, the EVs have to charge for 2 hours to be fully charged at 6:00, when the users need them. In this time period the total consumption of the 8 fast chargers is equal to 80 kW;
- from 6:00 to 22:00 the EVs are driven and the power injection/absorption of the fast chargers is equal to 0.

The active power of the fast chargers during week 9 is graphically shown in Figure 4.9.

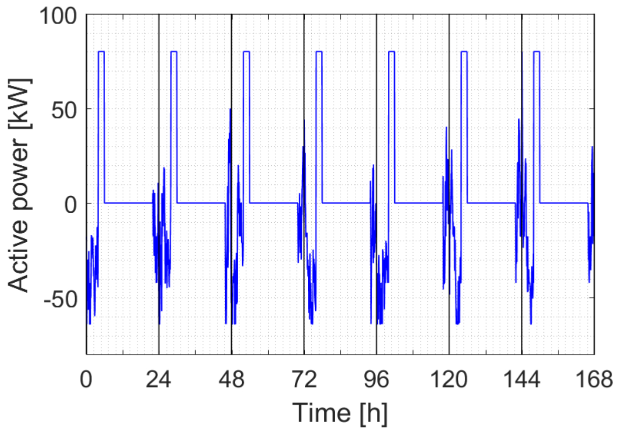


Figure 4.9: Active power of the 8 fast chargers, Rønne, week 9.

The reactive power consumption/absorption of the fast chargers is constantly equal to zero.

In the following analysis the fast chargers are considered as uncontrolled loads. They are already present in the grid, and they are not part of the percentage level of the EVs penetration.

4.5 Summary

After a brief introduction of the Bornholm power system, the chapter presented the grid topology and consumption characteristics of Tejn and Rønne, representative grids for Bornholm. Firstly the topology configuration of the two grids of Tejn and Rønne was described in detailed. Secondly the household consumption of both the grids was studied, comparing two winter weeks. In Tejn the household consumption was much more dependent on the outside temperature than in Rønne, due to the use of electric heating in some houses. Therefore the most loaded week 9 was chosen to be used for the following investigations. The reactive power of the households was determined as function of the $\cos\phi$, evaluated to be equal to 0.96. The phase loading analysis showed the presence of unbalances between the three phases. The unbalanced loading of the power system is approximated in both the grids as 40%, 30% and 30%, respectively on phases a, b and c.
Finally the fast chargers present in Rønne were described and their active power consumption/production was determined.

5 PowerFactory grid modelling

This chapter analyzes the grid modelling in DIgSILENT PowerFactory, software used for load flow analysis simulations. First a small introduction of the software is given, afterwards the implementation of the main components of the grid are analyzed, highlighting some solutions used during the grid modelling to overcome software limitations.

A goal of this project is to determine the feasibility and economic assessment of an alternative to grid reinforcement by drawing on EVs flexibility. The penetration of EVs in the system can cause overloading of present components and voltage deviation at the connection point. For this reason at the end of the chapter a charging control strategy for the EV penetration is also presented.

5.1 DIgSILENT PowerFactory

DIgSILENT PowerFactory (PF) is a calculation program to analyze transmission, distribution and industrial electrical power systems. PF modelling is targeted towards a strictly hierarchical system modelling approach, which combines both graphical and script-based modelling methods. The simulation functions used in this project are two: load flow analysis, that allows meshed and mixed 1-, 2- and 3-phase AC and/or DC networks and RMS simulation, a time-domain simulation for stability analysis [73].

Through the form of an unbalanced RMS procedure, a stability analysis is completed in PF comprising a multitude of power flows over a week-long term. Before the simulation starts, a logical load flow is carried out to determine the initial conditions for all the elements included in the modelled grid. The initial conditions depict the steady-state operating point at which the derivative of all state variables are zero. Defined by the simulation step size, in this project a power flow is calculated at intervals of:

- 300 seconds (5 minutes) for Tejn
- 60 seconds (1 minute) for Rønne

for a total of 604800 seconds (1 week). The different step size is due to the presence of the fast chargers in Rønne, which data are evaluated with one minute step.

The Danish LV grids are implemented and analyzed in PF using the grid layout of the models described in Section 4.2.

5.2 Household modelling

As described in Section 2.1.2 the majority of the houses in Denmark are connected to the main grid with 3-phase underground cables. These cables are usually overdimensioned and

paid/maintained by the customers, thus they are omitted in this analysis, which is mainly focused on the DSO perspective.
The graph representation of one household in PF is composed of three loads, one load represents one phase. To simulate the real consumption of the households over one-week period, the input of each load designed in PF is a text file (.txt). Each file has three columns: the first is the time, the second and third are vectors with active and reactive power consumption described in Section 4.3, and same length of the time. PF can read maximum $2^8 = 256$ external files during one RMS simulation. Therefore it is not possible to design each household with three loads, one per phase, because in both the study cases PF would have to read more than 256 files: 127 times 3 phases for the Tejn households and 110 times three phases for the Rønne households. Consequently, the households of each terminal are modelled as one combined household with three phases. Tejn has 54 terminals, Rønne has 40 terminals, thus the final amount of designed loads (and respective files) is 162 (one per phase) in Tejn and 120 (one per phase) in Rønne. The external files have still three columns, but now the active and reactive power is the sum of the household consumptions present in the terminal, split up between the three phases by setting: 40% in phase a, 30% in phase b and 30% in phase c. This distribution of the consumption between the three phases represents the unbalanced distribution of the currents between the three phases derived in Section 4.3.3.
Figure 5.1 and 5.2 illustrate an example of the PF model layout of the Rønne grid. Figure 5.1 shows the transformer and the four branches areas, Figure 5.2 illustrates a terminal that branches into other terminals. The three black loads, present in each terminal, are the combined loads of the terminals representing phase a, b and c. The fourth load named EV is the combined EV, of which the implementation is explained in Section 5.4.

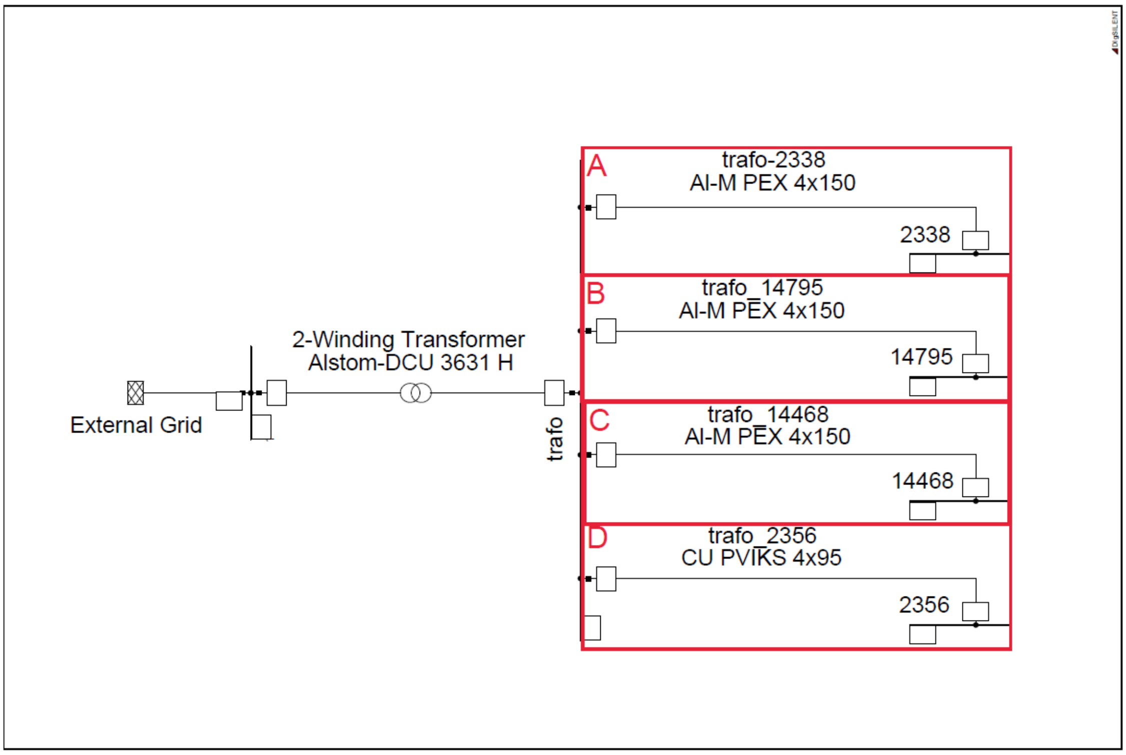


Figure 5.1: Graph representation of LV Rønne grid topology modelled in PF: St. 54.

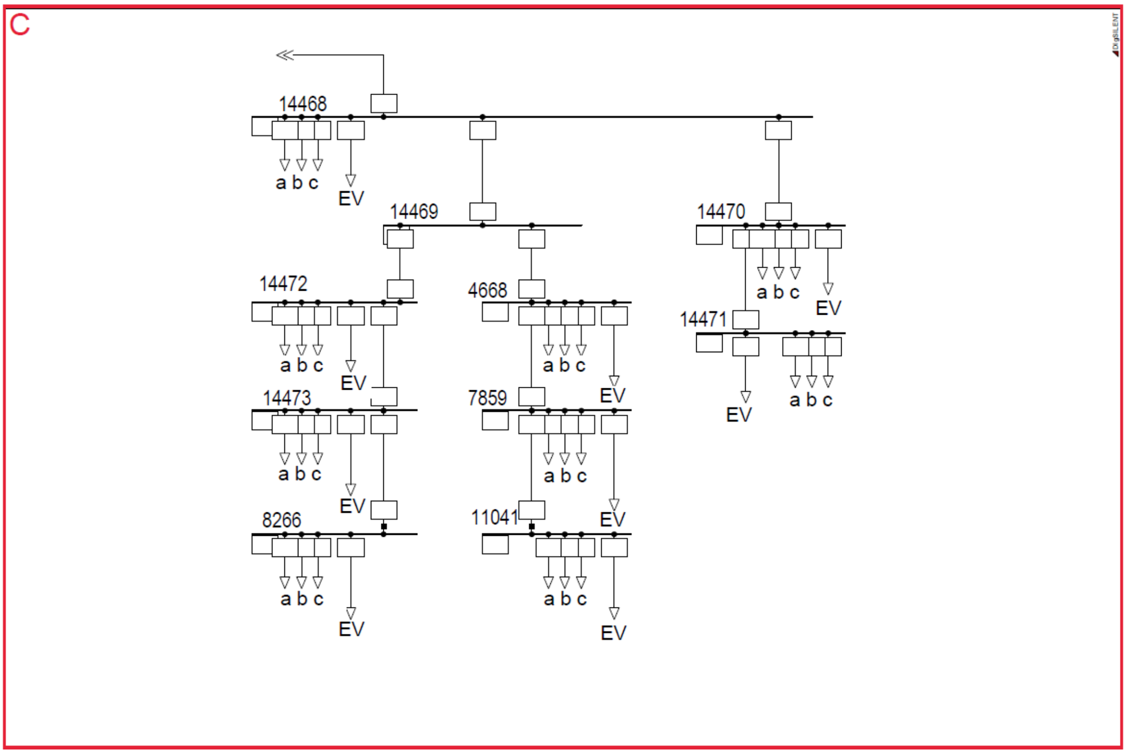


Figure 5.2: Graph representation of LV Rønne grid topology modelled in PF: Node 14468, area C.

5.3 Fast charger modelling

The 8 fast chargers are designed in PF using a three-phase load. As for the household consumption, the charger consumption is given to the PF load as external text file with three columns: time, active and reactive power consumption analyzed in Section 4.4.2.

Differently from the resistive loads, the fast chargers have constant power, therefore the active and reactive power absorption/injection does not depend on the voltage behaviour during the simulations.

5.4 Domestic charger modelling

The charging patterns designed in Section 3.3 are here used to implement the EV consumption of the domestic chargers in the PF models.

Four EV penetration levels are considered in this project: 100%, 75%, 50% and 25%. The 100% penetration means that every house has one EV. As the society is today, the 100% EV penetration is a long time distant case scenario. For this reason it is interesting to analyze lower representative penetration levels: 75%, 50% and 25%, detecting the issue characteristics that the EV penetration can bring in the power system. From 100% penetration, to lower the percentage level, the EVs are decreased in the various terminals, trying to preserve the homogeneity of the distribution of EVs through the grid. To this end, each penetration level is modelled from the 100%, removing more EVs from the terminals with higher amounts of EVs (and so households) and less from the ones with lower EVs. As for the household PF modelling, the EVs present in each terminal are combined into a single EV load. The graphical representation of the EVs in PF is a load and is kept the same for the considered penetration levels, as explained more in detail below. On the contrary the external files are changed in Matlab, because the consumption of the combined EV is the sum of the consumption of fewer amounts of EVs. The external files are very similar to the ones for the households and fast chargers. The considered EVs do not absorb or inject reactive power from/into the grid, thus the third vector is always equal to zero.

Taking into account the characteristics shown in Table 5.1 and the rated charging power of the chargers *Ch-1ph* and *Ch-3ph*, two types of load are used to model the combined EVs in PF.

Table 5.1: Number of households, terminals and EVs per penetration level in Tejn and Rønne.

	Number of households	**Number of terminals**	**Number of EVs**			
			25%	*50%*	*75%*	*100%*
Tejn	127	53	32	63	95	127
Rønne	110	39	28	55	82	110

When considering the **Ch-1ph** chargers, the EVs in each terminal are combined as one single EV load. The combined EV is connected to one phase a, b or c, thus all the EVs represented by the combined EV are charged with the same phase. To avoid loading of one phase more than the others, the combined EVs are distributed in the network among the three phases in a rotation way. In Tejn there are 53 terminals, meaning 18 combined EVs per each phase. In Rønne there are 39 terminals, meaning 13 combined EVs per each phase. When considering the 100% penetration, in Tejn there are circa 42[1] EVs per phase and in Rønne circa 37 EVs per phase. Each combined EV is the sum of the EVs in the terminal where the combined EV is located. The number of EVs combined in one EV (in a terminal) depends on the amount of households present in that terminal.

When considering the **Ch-3ph** chargers, the combined EVs are designed in PF using 3-phase loads. The EVs of each terminal are combined into one EV, and thanks to the 3-phase connection, the consumption is equally distributed between the phases. With this configuration, the study cases are analyzed only with 100% EV penetration.

The charging patterns with active power as designed in Section 3.3 and reactive power equal to zero, are the inputs of the combined EVs. The charging patterns are entered on the external files in a randomized way. This casual implementation is done to avoid particular case scenarios, where for example all EVs, which charge more and longer time periods, are located in one part of the grid. Thr graphical representation of the combined EVs is shown in Figure 5.2.

[1]This number represents the final amount of EVs per phase in the grid, which in PF are summed up in the 18 combined EVs.

5.5 Electric vehicle charging control: strategy and modelling

In this section a charging control strategy for EVs charged with single phase is designed.

Even though the EVs are integrated in PF using combined EVs, for simplicity the active power modulation is described for one single EV.

5.5.1 Active power modulation

This section describes the correlation between voltage and active power in LV distribution grids. The derivation of the formulas are provided in A.2 and A.3.
Distribution grids, as the ones considered in Figure 4.3 and 4.4 can be summarized as in Figure A.2.

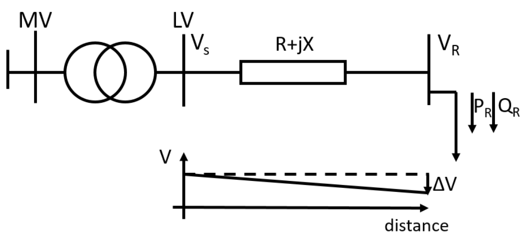


Figure 5.3: Relationship between P, Q and V in LV distribution grids. Adapted from [7].

The real component of the voltage drop across the feeder can be written as in equation 5.1:

$$\Delta V = \frac{RP_R + XQ_R}{V_R^*} \tag{5.1}$$

Considering:

- P_R^{PV} and Q_R^{PV}: active and reactive power injected by the PV panels to the grid (where present);
- P_R^L and Q_R^L: active and reactive power consumed by the householders from the grid;
- P_R^{EV}: active power consumed by the EVs from the grid. Q_R^{EV}, reactive power of the EVs is equal to zero.

Equation 5.1 is then rewritten as in A.12:

$$\Delta V = \frac{R(P_R^{PV} - P_R^L - P_R^{EV}) + X(Q_R^{PV} - Q_R^L)}{V_R^*} \tag{5.2}$$

The possibility of modulating the EV consumption to prevent grid congestion is here analyzed. In this project only the active power of the EV charging pattern is considered to be suitable to control. The idea is to modulate the active power of the EVs, assuming that the owners allow the DSO to change their charging patterns in return of reduced costs.

The active power modulation is implemented as a droop controller with current control mode. The idea of the controller is based on the two main equations of the power flow (derived in Appendix A.3):

$$P = \frac{V_S^2 - V_S V_R \cos\delta}{R} \quad (5.3) \qquad Q = \frac{-V_S V_R}{R}\sin\delta \quad (5.4)$$

Considering LV lines, $R >> X$ and $\sin\delta = \delta$, $\cos\delta = 1$, the two equations can be written as:

$$V_S - V_R = \frac{RP}{V_S} \quad (5.5) \qquad \delta = -\frac{QR}{V_R V_S} \quad (5.6)$$

From equation 5.5, in LV grids the voltage difference at the common connection point is more correlated to the active power. From equation 5.6 the variations of the power angle are more related to the reactive power. From equation 5.5 the control approach is defined considering that, when there is a voltage drop in the socket's connection, the EVSE understands that more active power is needed in the grid and the EV charging power is reduced. The active power is modulated by varying the charging current. The upper threshold is set to $0.95V_{nom}$, above this voltage the EVs charge at the maximum current of 16 A, meaning that only upward regulation is implemented[2]. The lower threshold is equal to $0.9V_{nom}$, where the current is kept equal to its minimum value of 6 A. Between the two values, the current is ideally linearly increased with $k = 5\%$, as slope coefficient of the droop control. In the PF model implementation, the current is realized with 10 steps, going from 6 to 16 A, as in Figure 5.4:

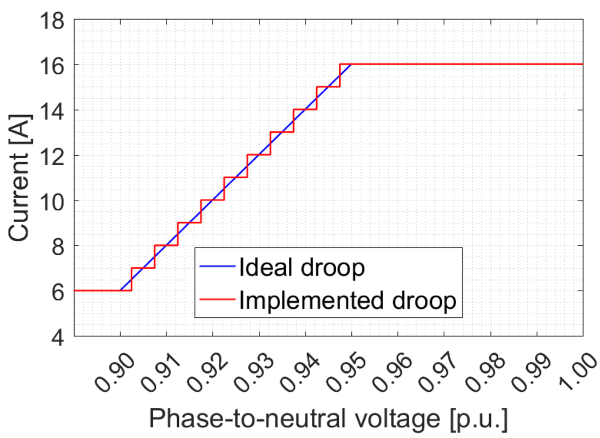


Figure 5.4: Ideal and implemented droop control, $k = 5\%$, for the active power modulation of the EV charging control strategy.

Since the EVs are implemented in PF as combined EVs, the unique difference from the described control is that the current implemented with the droop control is multiplied by the number of EVs present in the specific combined EV.
For more information about power modulation refer to [7, 12, 74].

5.5.2 EV composite frame implementation in PF

To model the active power modulation of the EVs in PF, the composite frame is used as illustrated in Figure 5.5:

[2]With these parameters the upward regulation is the regulation of the active power when the voltage is too low, in this case between 0.9 and 0.95 p.u.. The downward regulation is the regulation of the active power when the voltage is too high, for example it could be between 1.05 and 1.10 p.u..

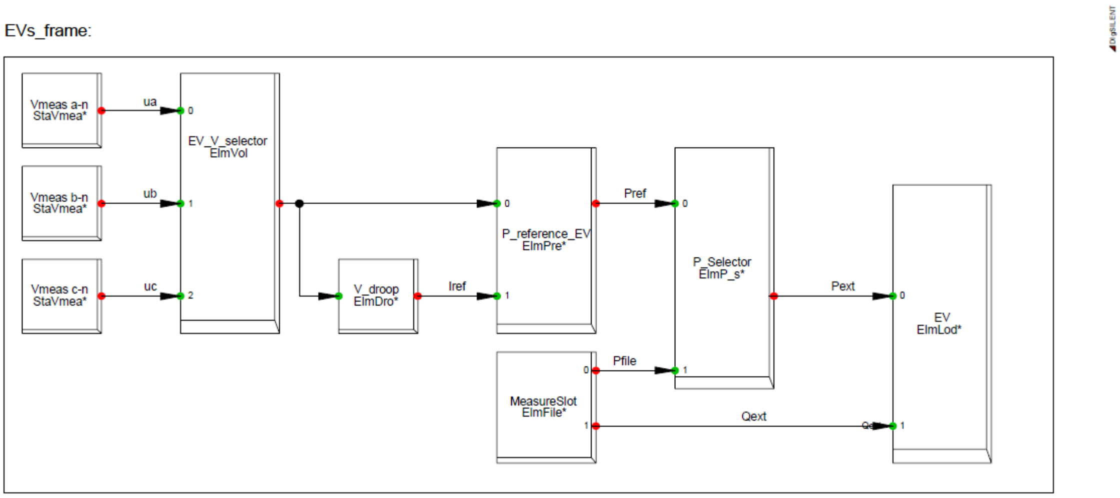


Figure 5.5: EV Composite Frame with P controller modelling in DIgSILENT PowerFactory.

The measurement slots (StaVmea*) measure the phase-to-neutral voltages (a, b and c). Since the same composite model is used for all the EVs, the voltage selector slot (ElmVol*) is implemented to select the measured voltage of the phase where the EV is connected. Another measurement slot (ElmFile*) is used to determine the signal P_{file}, as active power requested by the EVs and Q_{ext}, which is 0, for all the EVs, since no reactive power is consumed, absorbed or controlled. The voltage selected by the voltage selector slot enters into two other slots. The first one is the 'V_{droop}' slot, that works as droop for the active power control (ElmDro*) to determine a current reference set point as explained in 5.5.1. The second one is the power reference slot (ElmPre*), this receives as input the reference voltage and current (determined by the 'V_{droop}' slot) and it calculates the active power reference set point (P_{ref}) for the charging rate. The P_{ref} is then compared with the P_{file} in the power selector slot (ElmPse*), to evaluate the active power load value P_{ext} to set in the 'EV' slot:

$$P_{ext} = \begin{cases} P_{file} & \text{if } P_{file} < P_{ref} \\ P_{ref} & \text{if } P_{file} > P_{ref} \end{cases}$$

5.6 Summary

In this chapter the PF grid modelling has been analyzed. Firstly an introduction of the software was given. To overcome the software limitation on reading maximum 256 files during one simulation, the households and domestic chargers (as EVs) are modelled in PF using combined loads. The software does not distinguish an household and an EV, since they are both designed as single or three phase loads. Therefore the difference is seen from PF as consumption characteristic, given to the load with external text files. Differently from the previous resistive loads, the fast chargers have constant power. Finally, the single phase EV charging control strategy was presented, first with a brief introduction of the active power - voltage relationship, second with the PF modelling of the EV composite frame.

6 Technical results and sensitivity analysis

In this chapter, the technical results concerning the analysis of two Danish grids, Tejn and Rønne, are reported and discussed. First the parameters used to determine the power quality of the system are described, second the technical results of the analyzed scenarios are presented, including comparisons between the two grids.

6.1 Power quality parameters

The power system quality is identified by constancy of frequency and voltage. The power quality of a power system is continuously monitored to avoid unexpected events in the system that could cause remarkable economic losses. There are many power quality parameters that can be analyzed, but in this project the interest is focused on loading and losses of transformer and cables, and voltage behaviour of the most critical terminals. The first are chosen because of the EV penetration, which can interfere with the transformer and cable loading limits, the second is selected as one of the main parameters to assess the power quality of a system.

In the following parameter description, time t has steps of 300 seconds in Tejn and 60 seconds in Rønne, as explained in Section 5.1. The technical limitations and their relative studied parameters are:

- Transformer congestion limit: 100% loading.
  Mean and maximum transformer loading in percentage are investigated. First, the transformer loading in percentage is calculated as in equation 6.1:

  $$S_l(t) = \frac{S(t)}{S_{nom}} * 100 \tag{6.1}$$

  with $S(t)$ the apparent power at the transformer level at time t and S_{nom} the nominal apparent power of the transformer equal to 400 kVA.
  Second, mean and max values are carried out from the values in the two study cases.
- Cable congestion limit: 100% loading.
  Mean and maximum loading of the most critical cables, in percentage, are evaluated as average of the loading of the three phases. The maximum loading of the cables depends on the characteristics shown in Table 4.1.
- The power losses are defined as the sum of the transformer and cable losses.
  The losses are provided in this thesis as average active power losses in percentage (L_{mean}), total energy losses (E_{loss}) and delta losses (Δ_L):

L_{mean} is the mean value, of the active power losses evaluated in kW (P_L) and in percentage ($P_{L\%}$) as follows:

$$P_L(t) = P_t(t) - P_{sum} \qquad\qquad P_{L\%}(t) = \frac{P_L(t)}{P_t(t)} * 100$$

where $P_t(t)$ is the active power at the transformer level at time t, $P_{sum}(t)$ is the sum of the households and fast charger active power consumption at time t.

E_{loss} are the total energy losses that occur over one week. They are expressed in kWh.

Δ_L are the added losses of energy for charging caused by the EV penetration in the distribution grid. They are evaluated as difference between the E_{loss} of the analyzed scenario and the scenario without EVs. It is not including the charger loss.

- The nominal phase to neutral voltage in Denmark is 230 V. According to the European Standard, EN 50160 Voltage characteristics in Public Distribution Systems, the LV supply voltage must be within ±10% of the nominal voltage value for 95% of the week, measured in 10 minute RMS values and it can never go below 0.85 pu. In order to determine if the voltage limits have been exceeded, phase-neutral voltage measurements are completed at each node in the simulated grids for each analyzed scenario. The phase-to-neutral voltage is analyzed for the most critical terminals and it is given in p.u.. The voltage is presented using tables and boxplots[1], to better compare the differences between the scenarios. The boxplots is a standardized way of displaying the distribution of data and degree of dispersion. The values are defined over the one-week period and the tables quantify for how long the voltage is below the acceptable range of 0.9 p.u..

6.2 Investigated scenarios

The technical results are investigated, in Tejn and Rønne, for three main distinctive scenarios:

- **No EVs**: base case scenario without EVs, used to analyze the initial conditions of the two grids and to compare the present situation with the following scenarios.
- **Ch-1ph**: uncontrolled charging with four different EV penetration levels: 25%, 50%, 75%, 100%, using single-phase chargers.
- **Ch-3ph**: uncontrolled charging with 100% EV penetration level, using three-phase chargers.

The EV voltage control is also investigated in this thesis with the modulation of the active power, as explained in Section 5.5.1. Thus, it is assumed that EV owners allow the DSO to modify the charging patterns as active power control management, in return of charging cost reductions. This situation is investigated as a fifth scenario called **P control**, that is

[1] The boxplot shows the statistic of the result. In particular the box shows where 50% of the data is within, between 25% and 75% percentile quantile. The line in the middle of the box is the median. The top whisker shows the maximum value, excluding outliers that are further than 1.5 inter-quantile range from the 75% quantile. In the bottom the whisker has been modified from the standard whisker to show the 5% values below 0.90 p.u., meaning that 95% of the data is above the whisker (horizontal line).

a scenario *Ch-1ph* with 100% EV penetration with the implementation of the active power control droop for all the EVs.

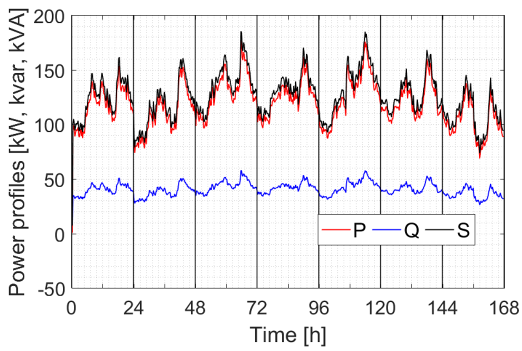
All the simulations are run for a one-week period: week 9, analyzed in Section 4.3.1. If not differently specified, figures and tables are always providing the results of the two study cases, Tejn and Rønne, for the considered week.

6.3 Scenario *No EVs*

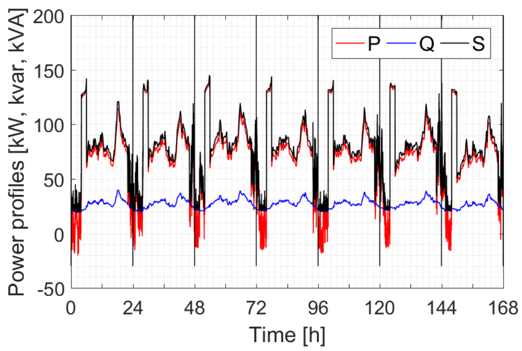
The base case *No EVs* scenario is used as a benchmark for the system. It is the current situation, where none of the modelled houses have EVs, only the household and fast charger consumption is considered.

Loading and losses analysis

Figure 6.1a and 6.1b compare the power profiles at the transformer level in the two grids of Tejn and Rønne respectively. As observed in Section 4, the transformer in Tejn is more loaded, on average, than the one in Rønne, but none of the two grids has congestion issues. Furthermore, in Rønne the active power at the transformer level is observed to become also negative during the frequency regulation of the fast chargers.



(a) Tejn



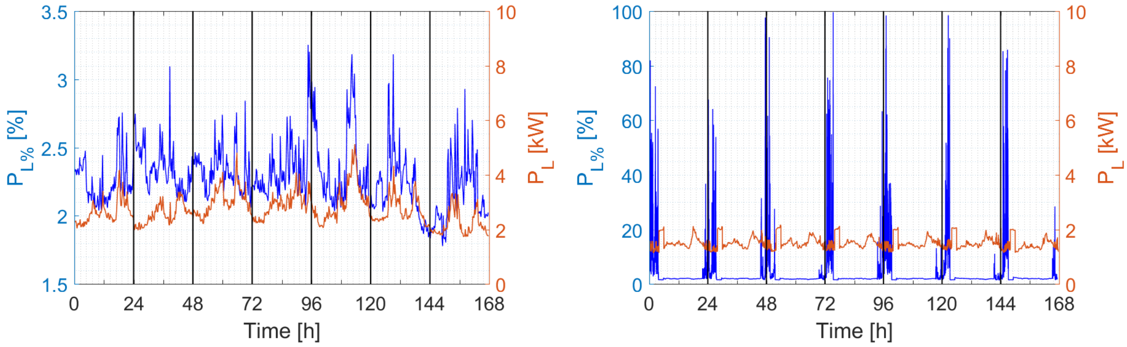
(b) Rønne

Figure 6.1: Transformer loading profiles for the two analyzed study cases. Scenario: *No EVs*.

In the base case scenario, no overloading of the cables is observed in the two grids. Nevertheless, for each grid one cable is more loaded than the others:

- Tejn: the most loaded cable is the one that connects the transformer to terminal 10058 in area A, shown in Figure 4.3. The author will refer to this cable using the name "*St-10058*". The cable is a 4x95 Al of 50 m. The maximum and mean loading values during the week are 51.6% and 26.9%, respectively.
- Rønne: the most loaded cable is the one that connects the transformer to terminal 2338 in area A, shown in Figure 4.4. The author will refer to this cable using the name "*St-2338*". The cable is a 4x150 Al-M PEX of 10 m. The maximum and mean loading values during the week are 38.5% and 19.5%, respectively.

In Figure 6.2a and 6.2b the active power losses in percentage $P_{L\%}$ (left y-axis) are compared with the active power losses in kW P_L (right y-axis), for the two analyzed grids. In Tejn, the average of the losses in percentage or kW is similar: 2.29% and 2.71 kW. In Rønne, the values are 3.95% and 1.50 kW. The percentage values are biased by the active power absorption/injection of the fast chargers during the frequency regulation from 22:00 to 4:00. The fast chargers inject active power into the system for most of the time during the night (see Figure 6.1b), thus the active power at the transformer level becomes negative or very close to zero. When the transformer is very low loaded, the losses in percentage ($P_{L\%}$) increase, showing high peaks as in Figure 6.2b. To avoid biased results, in Rønne the following analyses are based on the percentage value from 4:00 to 22:00, without the values with frequency regulation of the fast chargers. In this situation the L_{mean} is 1.90%.



(a) Tejn (b) Rønne

Figure 6.2: Comparison of the active power losses in percentage ($P_{L\%}$) and kW (P_L) for the two grids. Scenario: *No EVs*.

In the analyzed grids the percentage losses are found to be approx. 2-3%, whereas in distribution grids, the percentage losses are usually between 3% and 5% [75] (4-6% in Denmark [16]), approximately 1-2% for the transformer losses and the rest for the cable losses. The results of the Bornholm grids show lower values than the Danish average, due to two reasons. First, some simplifications of the reality are used for the grid modelling in PowerFactory, as described in Chapter 5. Second, the characteristics of the components, such us cables, highly depend on unpredictable external factors, increasing the difficulties on modelling and feature choices.

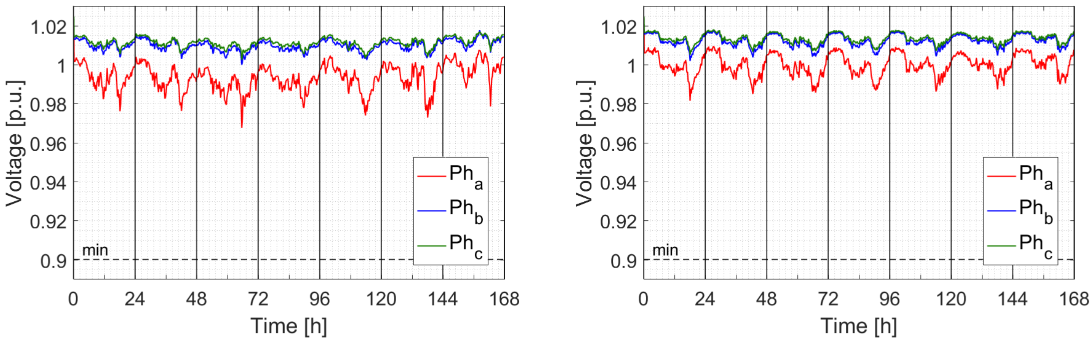
Voltage magnitude and unbalance

From the voltage analysis, the most critical terminals of the two grids are found to be:

- terminal 4379 in Tejn
- terminal 2352 in Rønne.

Both these terminals are located at the end of the grids, as seen in Figure 4.3 and 4.4, experiencing the cumulative impact of the additional voltage drops by the households at each node closer to the transformer.
Figure 6.3a and 6.3b show the voltage profile of the two terminals, 4379 and 2352 respectively. As aforementioned, both the grids operate in unbalanced conditions, since the power flow is shared between the three phases, 40% in a, 30% in b and 30% in c. As expected, *phase a*

is the one with lower voltage values, but still far away from the minimum limit of 0.9 p.u.. In Tejn the voltage on the three phases has lower values than the one in Rønne, due to larger household consumption.



(a) Tejn: 4379 (b) Rønne: 2352

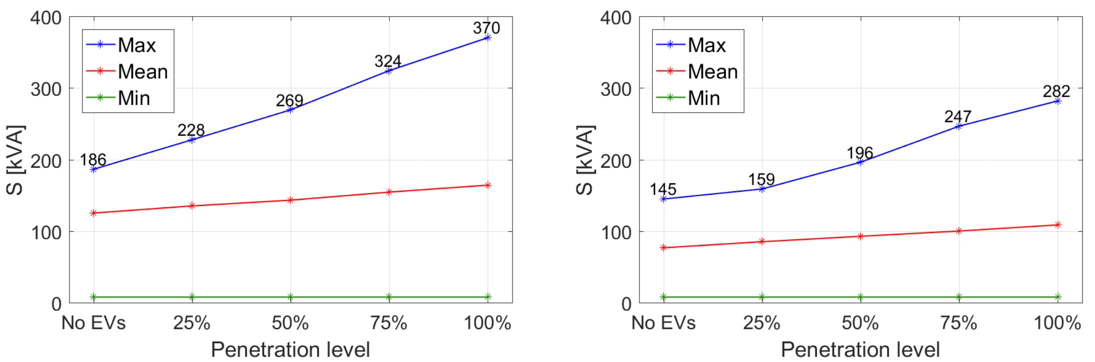
Figure 6.3: Phase-to-neutral voltage magnitude *phase a*, *b*, and *c* of the most critical terminals. Scenario: *No EVs*.

6.4 Scenario *Ch-1ph*

6.4.1 Comparison of 25%, 50%, 75%, 100% EV penetration levels

This section compares the four penetration levels of 25%, 50%, 75%, 100% with *Ch-1ph* and with the base case called *No EVs*, as 0% penetration level.

Loading and losses analysis

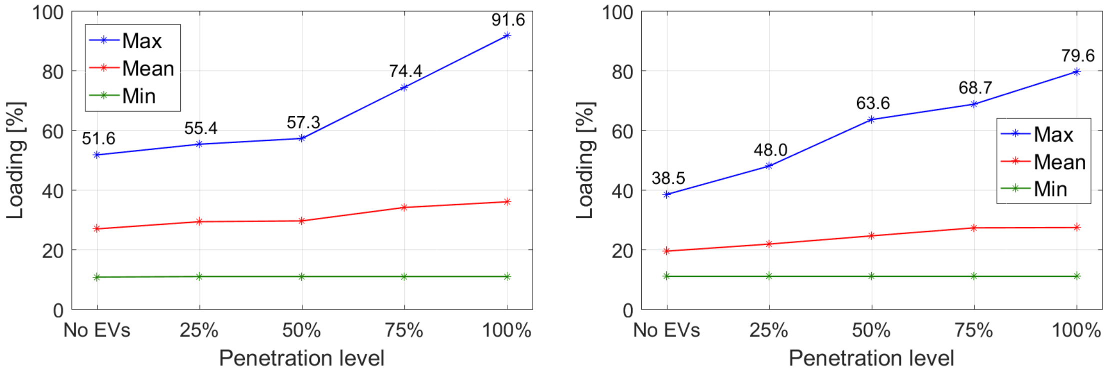


(a) Tejn (b) Rønne

Figure 6.4: Comparison apparent power at the transformer level with 0% (No EVs), 25%, 50%, 75%, 100% EV penetration levels.

Figure 6.4a and 6.4b show the max, mean and min apparent power values at the transformer level, in Tejn and Rønne respectively during one week. For both the transformers, the apparent power never reaches the rated power of the transformer (400 kVA) and the max apparent power increases linearly with higher penetration levels. The same is the case for the mean values, but in this case the curves are less steep. This is due to the fact that

the max values are reached during the EV charging peak (circa 18:00), which coincides with the peak consumption of the households. Differently, the mean values are partially influenced by the charging time, as the values are the average of the entire week.
As for the base case scenario, the most loaded cables are *St-2338* in Rønne and *St-10058* in Tejn. Max, mean and min values of the cable loading are provided in Figure 6.5a and 6.5b for Tejn and Rønne respectively. Similarly to the transformer loading, the max and mean loading of the cable increase almost linearly, with larger EV penetration levels. "Almost" because when there are few EVs, the probability that they charge concurrently is lower and, as consequence, the loading of the cable reaches lower maximum. The max loading values show that the cables are never overloaded in any of the analyzed grids.



(a) Tejn: cable *St-10058*

(b) Rønne: cable *St-2338*

Figure 6.5: Comparison of specific cable loading with 0% (No EVs), 25%, 50%, 75%, 100% EV penetration levels.

The L_{mean}, E_{loss} and Δ_L values for the two analyzed grids are presented in Table 6.1. As for the transformer loading, L_{mean} and E_{loss} increase linearly with the increase of the penetration level. It is important to point out that the L_{mean} does not increase dramatically, even for 100% EV penetration. For every 25% increment of penetration, the percentage increase of E_{loss} is of 13-16% from the previous value, and the losses E_{loss} are almost doubled going from the *No EVs* scenario to the 100% penetration.

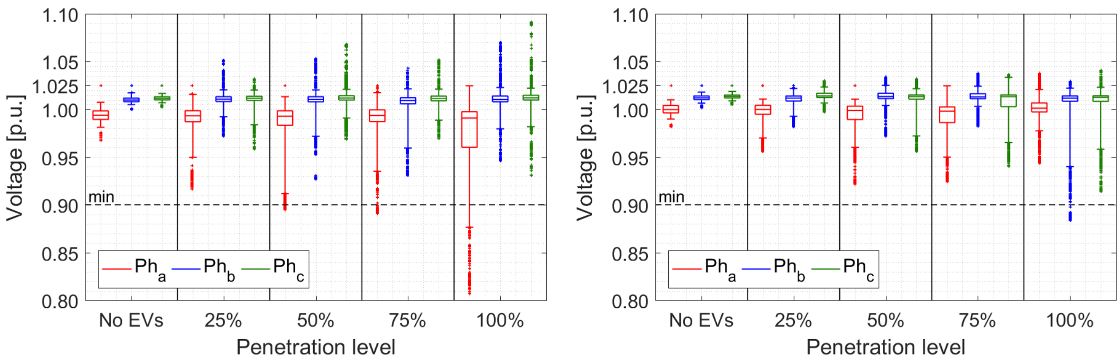
Table 6.1: L_{mean}, E_{loss} and Δ_L values of the two grids with 0% (No EVs), 25%, 50%, 75%, 100% EV penetration levels.

	Losses					
	Tejn			***Rønne***		
	$\mathbf{L_{mean}}$ [%]	$\mathbf{E_{loss}}$ [kWh]	Δ_L [kWh]	$\mathbf{L_{mean}}$ [%]	$\mathbf{E_{loss}}$ [kWh]	Δ_L [kWh]
No EVs	2.29	455	0	1.90	253	0
25%	2.37	517	62	1.96	292	40
50%	2.46	582	127	2.02	329	77
75%	2.53	663	208	2.07	374	122
100%	2.63	770	315	2.15	429	176

Voltage magnitude and unbalance

As in scenario *No EVs*, with EV penetration 4379 and 2352 are still the terminals with the lowest voltages in Tejn and Rønne respectively. It is important to investigate also the

other end-terminals. For example in Rønne, terminal 2358 (parallel to 2352 as shown in Figure 4.4) experiences better voltages than 2352, but depending on the charging pattern displacement, 2358 could be worse than 2352.
Figure 6.6a and 6.6b show the voltage of *phases a*, *b* and *c* in terminals 4379 and 2352, Table 6.2 quantifies the time of under-voltage values shown in the figures. The two terminals are still the worst terminals for both the analyzed grids. In Tejn, the 0% and 25% penetrations do not result in under-voltages. When the penetration level is higher, *phase a* has under-voltage values, but only with 100% penetration the voltage is below 0.9 p.u. for more than 5% of the time, with minimum of 0.81 p.u. and under-voltage time for 10.3% of the week. On the contrary, *phase b* and *c* reach values of 1.06-1.07 p.u., showing unbalances between the three phases. In Rønne, only with 100% penetration *phase b* experiences under-voltage values for 1.07% of the week with minimum of 0.88 p.u.. The analyzed scenarios show that Rønne is more balanced than Tejn.



(a) Tejn: 4379

(b) Rønne: 2352

Figure 6.6: Comparison of voltage *phase a*, *b* and *c*, of the most critical terminals, with - 0% (No EVs), 25%, 50%, 75%, 100% - EV penetration levels.

Table 6.2: Under- voltage (V < 0.90 p.u.) time period: *Phase a* in Tejn, *Phase b*, Rønne:

Under- voltage V < 0.90 p.u. time							
Tejn: 4379 Ph_a						***Rønne: 2352*** Ph_b	
50%		*75%*		*100%*		*100%*	
[h]	[%]	[h]	[%]	[h]	[%]	[h]	[%]
1.74	1.04	1.83	1.09	17.3	10.3	1.80	1.07

The transformer loading is linearly increasing with higher EV penetrations, whereas a similar linearity is not found with the voltage. This is because the voltage magnitude is much more dependent on the phase connection of the EVs through the grid. The grids were already unbalanced for the household consumption in the base case scenario and the EVs introduce additional unbalances, not only due to the single-phase connection, but also for the differences between the charging patterns, randomly distributed in the grid. Even though transformer and cables would be able to supply all the customers for EV penetration up to 100%, under-voltage outliers are observed between 25% and 50% penetration in Tejn and 75% and 100% in Rønne. Nevertheless, 100% penetration in Tejn is the only scenario that overcomes the limits of voltage (0.85 p.u.) and time (5%) during the analyzed week.

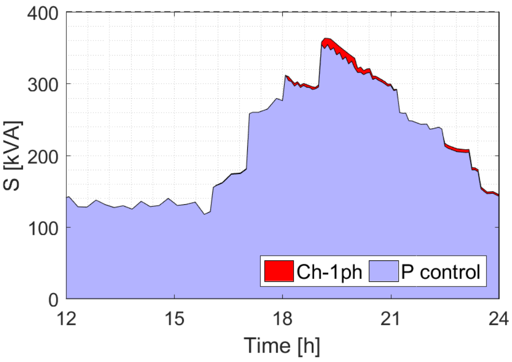
The following analysis is focused on the 100% penetration level, therefore when referring to scenario *Ch-1ph*, the author will be referring to the just analyzed 100% penetration scenario.

6.4.2 Scenario comparison: *Ch-1ph* and *P control*

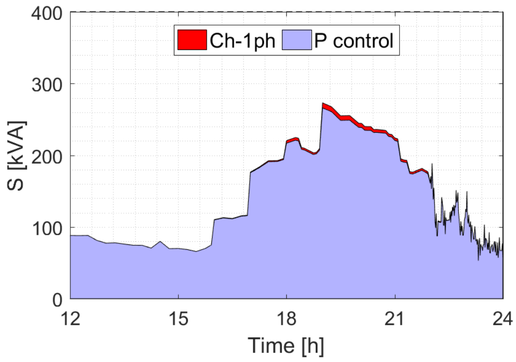
This section is dedicated to the comparison between scenarios *Ch-1ph* and *P control*, both have 100% EV penetration. The *P control* is the scenario with the implementation of the EV active power modulation: the EV reduces the charging power when measuring low voltages at the point of connection. The energy is only decreased when the voltage is low (that corresponds with the peak consumption), but not moved afterwards, meaning that the final energy consumption is lower. This is because the different charging patterns and the used software PowerFactory would have made the implementation highly time-consuming. Nevertheless, since the scenario *Ch-1ph* did not present many hours of under-voltage values during the week, the results are not expected to be too different, as it is shown afterwards.

Loading and losses analysis

Figure 6.7a and 6.7b show the apparent power at the transformer for the two scenarios, from 12:00 to 24:00 of Wednesday. The rest of the week is similar to Wednesday, showing a very small moved energy in both the study cases. This explains that, even though the energy is not added in the simulation in another moment of the day, the results will not change a lot.



(a) Tejn



(b) Rønne

Figure 6.7: Example apparent power at the transformer from 12:00 to 24:00 of Wednesday. Scenarios: *Ch-1ph* and *P control*.

Table 6.3: Max and mean transformer loading for the study cases. Scenarios: *Ch-1ph* and *P control*.

	Transformer loading			
	Tejn		***Rønne***	
	mean [%]	**max** [%]	**mean** [%]	**max** [%]
Ch-1ph	41.4	93.5	27.2	70.5
P control	40.8	88.6	27.0	68.8

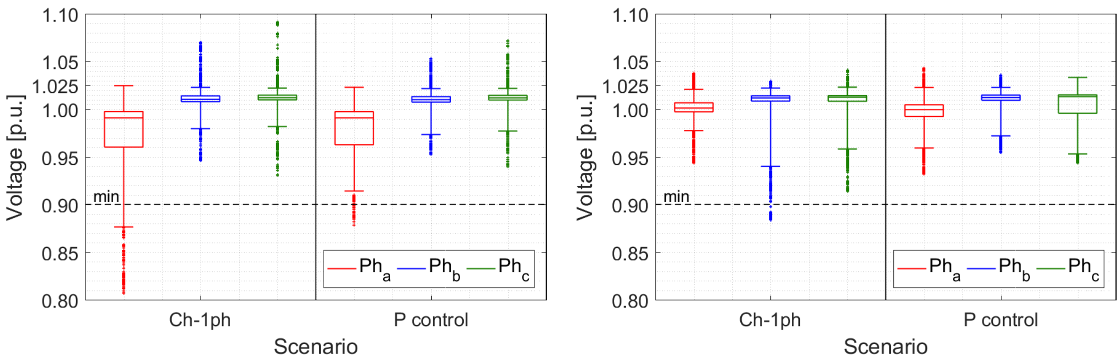
Table 6.4: L_{mean}, E_{loss} and Δ_L values of the two study cases. Scenarios: *Ch-1ph* and *P control*.

	Losses			
	Tejn		***Rønne***	
	$\mathbf{L_{mean}}$ [%]	$\mathbf{E_{loss}}$ [kWh]	$\mathbf{L_{mean}}$ [%]	$\mathbf{E_{loss}}$ [kWh]
Ch-1ph	2.63	770	2.15	429
P control	2.54	716	2.11	415

Table 6.3 compares mean and max transformer loading values of the two grids in scenarios *Ch-1ph* and *P control*. In scenario *P control* the active power flow in the transformer is lower, both as max and mean loading values, than in scenario *Ch-1ph*.
With *P control* there is no overloading of the cables and the cable loading is lowered similarly to the transformer loading. Indeed with *P control* the maximum loading of cable *St-10058* in Tejn is 83.4% (*Ch-1ph*: 91.6%) and of cable *St-2338* in Rønne is 73.9% (*Ch-3ph*: 79.6%). The losses are also decreased as shown in Table 6.4. The difference between the E_{loss} of the two scenarios is higher in Tejn than in Rønne, showing that the active power is modulated more in Tejn than Rønne. The active power is changed because of the voltage control, that reaches lower values in Tejn. A small part of the decreased losses is also caused by the moved energy that is not considered afterwards in time.

Voltage magnitude and unbalance

Figure 6.8a and 6.8b show the voltage of the three phases at the worst terminal, in Tejn and Rønne respectively. In scenario *Ch-1ph* Tejn, *phase a* is below 0.9 p.u. for approx. 17.3 h. With the active power modulation *phase a* still has low voltage values, but the minimum value is 0.87 p.u. and the voltage is below 0.9 p.u. for 3.66 h (2.18%). In Rønne, from having 1.80 hours of low-voltage values in *phase b*, with the active power modulation the phases do not exceed the limits. It can be concluded that the minimum voltage is improved in the *P control* scenario for both the grids. In Tejn the active power is modulated for a longer time period than in Rønne, even though some under-voltage outliers are still observed.



(a) Tejn: 4379

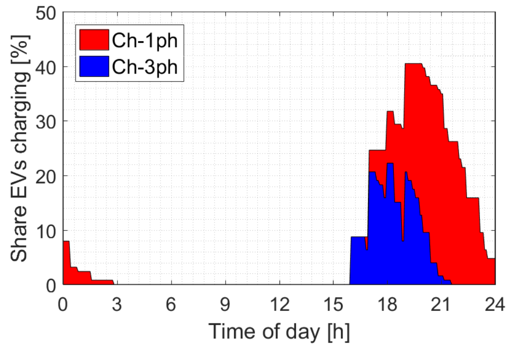
(b) Rønne: 2352

Figure 6.8: Voltage in the three phases of the most critical terminals. Scenarios: *Ch-1ph* and *P control*.

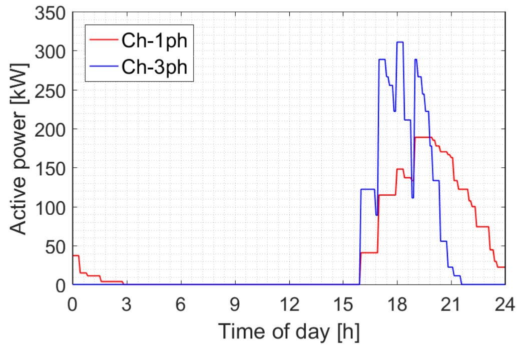
6.5 Scenario comparison: *Ch-1ph* and *Ch-3ph*

Charging pattern

This section compares the EVs charging pattern characteristics in scenarios *Ch-1ph* and *Ch-3ph*. The active power consumption is different if using Ch-1ph or Ch-3ph chargers, while the consumed energy is the same. Figure 6.9a compares the share of EVs charging during one-day (Monday) for the two scenarios.



(a) Percentage EVs charging.



(b) Sum EVs active power consumptions.

Figure 6.9: Charging patterns comparison, one-day period, Tejn. Scenarios: *Ch-1ph* and *Ch-3ph*.

The example considers a total of 127 EVs in Tejn, but even with more EVs, the model responds in a similar way, showing a maximum of 40-45% EVs charging simultaneously in *Ch-1ph* scenario and 20-25% in *Ch-3ph* scenario. In Figure B.1a (Appendix B), the same is shown for the week-long period. Figure 6.9b illustrates the sum of the active power consumptions of the 127 EVs on the same day in the two scenarios. With Ch-1ph chargers the EVs charge for longer periods, thus more EVs get to charge concurrently. The maximum active power is 200 kW during the whole week with Ch-1ph chargers, and 323 kW with Ch-3ph chargers, showing that even though the individual EV consumption is tripled, the combined peak is not even doubled since only 20-25% EVs get to charge concurrently. Finally, it is important to notice that the maximum consumption peak is reached between 18:00 and 20:00, period of time that corresponds to the domestic electricity peak consumption (see Figure 6.1a).

Loading and losses analysis

Table 6.5 provides mean and max transformer loading values for the compared scenarios and analyzed study cases.

Table 6.5: Max and mean transformer loading of the two study cases. Scenarios: *Ch-1ph* and *Ch-3ph*.

	Transformer loading			
	Tejn		***Rønne***	
	mean [%]	**max** [%]	**mean** [%]	**max** [%]
Ch-1ph	41.4	93.5	27.2	70.5
Ch-3ph	40.8	120	28.0	99.5

Tejn is the most loaded transformer in the considered scenarios. In *Ch-3ph* scenario the transformer is overloaded for 9.25 hours (555 minutes). The transformer in Rønne does not experience overloading in scenario *Ch-3ph*, but the max value is 99.5%, very close to the limit.
In Table 6.6 the max and mean cable loading are shown. The most loaded cables in the two scenarios are always the same: *St-10058* in Tejn and *St-2338* in Rønne. With three

phase chargers both the cables are overloaded: in Rønne for only 0.2 h (11 min) with max value of 102%, in Tejn for 2 h with max value of 116%. Moreover, in Tejn not only the cable closest to the station experiences congestion issues, but also the one that connects terminal 10058 to 10059 in area A, see Figure 4.3. Cable 10058-10059 is overloaded for 0.42 h (25 min), with maximum overloading of 108%.

Table 6.6: Max and mean cable loading of the two study cases. Scenarios: *Ch-1ph* and *Ch-3ph*.

	Cable loading					
	Tejn: St-10058			***Rønne: St-2338***		
	mean [%]	**max** [%]	**time** [h]	**mean** [%]	**max** [%]	**time** [h]
Ch-1ph	36.0	91.6	0	27.4	79.6	0
Ch-3ph	34.7	116	2.0	28.3	102	0.2

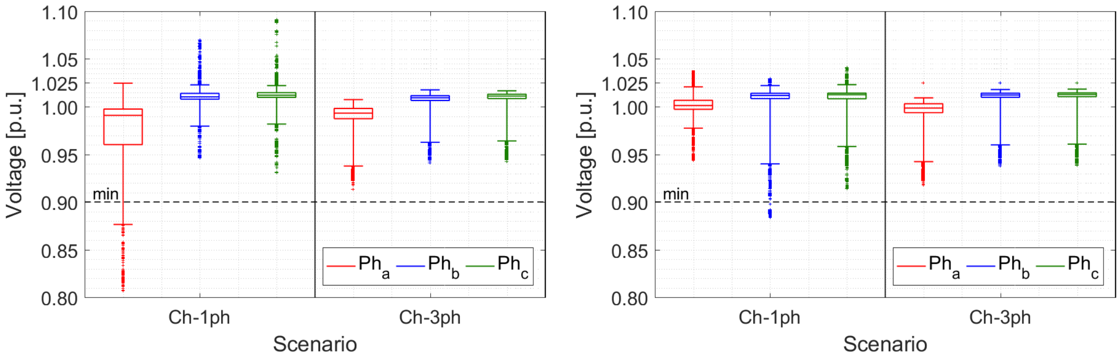
Table 6.7 provides the active power losses. The L_{mean} values are always in the same range, slightly lower for Rønne than Tejn. With 100% EV penetration the E_{loss} are almost doubled if compared to scenario *No EVs*. The difference between E_{loss} of *Ch-1ph* and *Ch-3ph* in Tejn is circa 80 kWh, whereas in Rønne the values are similar. As aforementioned, Tejn in scenario *Ch-1ph* is more unbalanced than Rønne, even though both the grids were designed with the EVs equally distributed over the phases. Nevertheless, due to their single-phase connection the EVs introduce unbalances in scenario *Ch-1ph* that are more evident in Tejn, since the losses in *Ch-3ph* are lower. In Rønne the E_{loss} of the two scenarios are not very different, showing that the grid with Ch-1ph chargers is not badly unbalanced as the one in Tejn.

Table 6.7: L_{mean}, E_{loss} and Δ_L values for the two study cases. Scenarios: *Ch-1ph* and *Ch-3ph*.

	Losses					
	Tejn			***Rønne***		
	$\mathbf{L_{mean}}$ [%]	$\mathbf{E_{loss}}$ [kWh]	$\Delta_\mathbf{L}$ [kWh]	$\mathbf{L_{mean}}$ [%]	$\mathbf{E_{loss}}$ [kWh]	$\Delta_\mathbf{L}$ [kWh]
Ch-1ph	2.63	770	315	2.15	429	176
Ch-3ph	2.43	692	237	2.05	432	180

Voltage magnitude and unbalance

Terminal 4379 in Tejn and 2352 in Rønne are the most critical terminals in the analyzed scenarios. Figure 6.10a and 6.10b illustrate the voltage magnitude of the three phases, for the conducted scenarios in Tejn and Rønne respectively. Unlike the congestion analysis, the worst scenario is *Ch-1ph*. As aforementioned, *phase a* is the most critical phase in Tejn in scenario *Ch-1ph*, and *phase a* is the most critical phase in Rønne. Differently in *Ch-3ph* scenario, since the EVs charge on three-phases, the phases are almost balanced, "almost" because there is still a unbalanced loading distribution between the three phases of the household consumption.



(a) Tejn: 4379

(b) Rønne: 2352

Figure 6.10: Voltage in the three phases of the most critical terminals of the two study cases. Scenarios: *Ch-1ph* and *Ch-3ph*.

6.6 Sensitivity analysis

The aim of this section is to evaluate how the variations of some key parameters influence the rest. The sensitivity analysis is divided in three subsections that investigate the grids changing the following parameters:

- The EV distribution on the three phases, with single phase chargers, 33%-33%-33% phases a, b, c, is modified to 50%-25%-25%.
- Each EV has a charging pattern and the specific location of the EVs are moved around.
- The plug-in charging time of all the EVs is moved to 20 to simulate the effect of a ToU tariff.

The rational behind the choice of the mentioned input is explained in each section.

6.6.1 Uneven EV charging on the three phases

In this section the importance of the EV connection on the three phases, when the single phase chargers are used, is shown. The EVs are distributed among the three phases in a rotation way, 33% share of EVs per phase. The equal distribution is important to minimize unbalances, which have been shown to be present due to the different charging patterns of the EVs. Scenario *Ch-1ph* is named "balanced" in this section, since the EVs are equally distributed on the three phases. The balanced scenario is compared with an "unbalanced" case, equal to scenario *Ch-1ph* but with the EVs connected to the three phases with 50%/25%/25% on phases a, b and c.

Loading and losses analysis

The effect on the transformer in the balanced and unbalanced scenario are similar both in terms of mean than max values. In the unbalanced case, in Tejn the maximum transformer loading is 94.7% (93.4% in the balanced *Ch-1ph*), whereas in Rønne it is 68,7% (70.5% in the balanced *Ch-1ph*).
Differently is the situation for the cable loading. As shown in Table 6.8, in Rønne the

most loaded cable is still *St-2338*, with higher but not overloaded values in the unbalanced case. In Tejn the situation is more critical to detect, indeed cable *St-10058*, with max loading of 84.8% is not the most loaded. In the unbalanced scenario the most loaded cable is the one that connects the station to terminal 10120 (Figure 4.3). In none of the previous scenarios cable *St-10120* had congestion problems, but with the unbalanced distribution of the EVs on the three phases the overloading of this cable lasts for approx. 4 hours, with a maximum loading of 113%. Due to the unbalance increase the losses rise as well as quantified in Table 6.9.

Table 6.8: Mean and max cable loading cables *St-10058*, *St-10120* in Tejn and *St-2338* in Rønne. Comparison balanced and unbalanced EV location of scenario *Ch-1ph*

	Cable loading					
	Tejn: St-10058		***Tejn: St-10120***		***Rønne: St-2338***	
	mean [%]	**max** [%]	**mean** [%]	**max** [%]	**mean** [%]	**max** [%]
Balanced	36.0	91.6	24.5	68.0	27.4	79.6
Unalanced	36.1	84.8	31.2	113	29.5	93.5

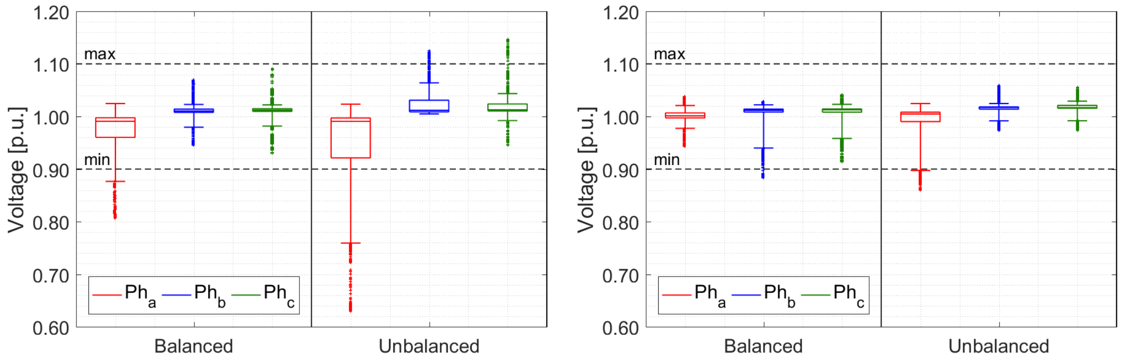
Table 6.9: L_{mean} and E_{loss} values for the two study cases, comparison balanced and unbalanced EV location of scenario *Ch-1ph*.

	Losses			
	Tejn		***Rønne***	
	$\mathbf{L_{mean}}$ [%]	$\mathbf{E_{loss}}$ [kWh]	$\mathbf{L_{mean}}$ [%]	$\mathbf{E_{loss}}$ [kWh]
Balanced	2.63	770	2.15	429
Unbalanced	2.91	911	2.23	454

Voltage magnitude and unbalance

The voltage mainly shows the issue caused by the uneven distribution of the EVs on the three phases. Figure 6.11a and 6.11b illustrate the voltage magnitude comparing balanced and unbalanced case for the most critical terminals. Table 6.10 quantifies the amount of time that the voltage in each phase is below 0.90 p.u. or above 1.10 p.u.. The most critical terminals in the unbalanced case[2] are still 4379 in Tejn and 2352 in Rønne. In Tejn the unbalanced case shows a completely disequilibrium between the phases: *phase a* has values to 0.63 p.u., *phases b* and *c* have high-voltage outliers to 1.15 p.u.. In the unbalanced case *phase a* has under-voltage values for a double period of time in comparison to the balanced case. In Rønne the situation is similar, but more moderated than in Tejn. Indeed only *phase a* has under-voltage values and no voltage values above 1.10 p.u. are observed. The voltage is below 0.9 p.u. for 5.42 % (9.11 h) of the week, above the EU Standard of 5%.

[2]Only the values of the worst terminals are provided in this report, nevertheless more than one terminal per grid were observed to have under-voltage values in the unbalanced case scenario.



(a) Tejn: 4379 (b) Rønne: 2352

Figure 6.11: Voltage on the three phases for the most critical terminal in each grid. Comparison balanced and unbalanced EV connection of scenario *Ch-1ph*.

Table 6.10: Over- Under- voltage (V > 1.10 p.u., V < 0.90 p.u.) time period for the two study cases. Comparison balanced and unbalanced EVs location of scenario *Ch-1ph*.

	Over- Under- voltage (V > 1.10 p.u., V < 0.90 p.u.) time											
	Tejn: 4379						***Rønne: 2352***					
	Ph_a		Ph_b		Ph_c		Ph_a		Ph_b		Ph_c	
	[h]	[%]	[h]	[%]	[h]	[%]	[h]	[%]	[h]	[%]	[h]	[%]
Balanced	17.3	10.3	0	0	0	0	0	0	1.80	1.13	0	0
Unbalanced	36.8	21.9	5.00	2.98	3.00	1.79	9.11	5.42	0	0	0	0

It is concluded that with different charging patterns, an equal distribution on the three phases is necessary to avoid voltage issues and cable overloading with 100% EV penetration.

6.6.2 Relocation of the specific EVs

Since the EVs have different charging patters, it is interesting to know which is the impact on the grid of different location of the EVs. This analysis is applied to the four penetration levels - 25%, 50%, 75% and 100% - analyzed in Section 6.4.1. Three distributions α, β and γ, for each penetration, are simulated with a different location of the EVs through the grid. Distribution α is the one presented in Section 6.4.1. The other two distributions, per each penetration level, have different locations of the EVs in the terminals. The amount of EVs per terminal and the charging phase are kept the same. For example, considering 100% penetration level: a terminal with 4 EVs, have different charging patterns for the 3 distributions (α, β, γ), but the number and the charging phase of the EVs are the same. The location of the average driven kilometres of the individual EV owner is unknown, therefore the three distributions give the possibility to observe different dispositions of the charging patterns, trying to answer to the question: how sensitive are the simulation results to the specific configuration of the charging patterns?

Loading and losses analysis

Table 6.11 provides the mean and max transformer loading, Table 6.12 lists the L_{mean} and E_{loss} of the three distributions with different penetration levels. An AVG value is also shown as average of the three distributions. The transformer loading has very similar

loading in the three distributions of the different penetration levels. The same can be said for the cable loading, which are similar to the analyzed α in Figure 6.5. The most critical cables are always *St-10058* in Tejn and *St-2338* in Rønne for all the analyzed distributions and the values are provided in Appendix B Table B.1. The consumed energy by the households and EVs is the same in the three distributions of each penetration, nevertheless a small difference between the overloading values can be observed. This is due to the nonconformity losses of the cables, which change depending on the location of the EVs. The same can be observed for the energy losses.
The reason is better explained with an example. When an EV charges every evening for three hours in one of the terminals closer to the transformer, the active power flows through few cables (short distance). When the EV is in one of the end terminals, the active power flows through more cables (long distance). When the current flows in shorter or fewer cables, the losses are lower.

Table 6.11: Comparison mean and max transformer loading, distributions α, β, γ. Scenario *Ch-1ph*: 25%, 50%, 75%, 100%.

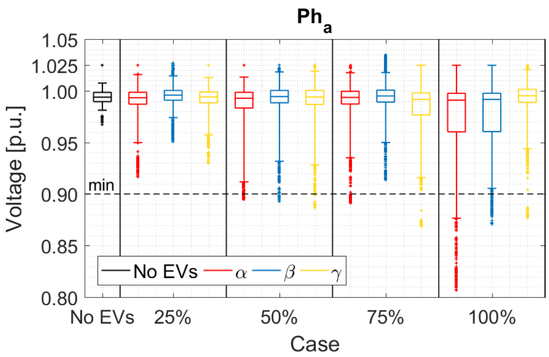
	Transformer loading			
	Tejn		***Rønne***	
	mean [%]	**max** [%]	**mean** [%]	**max** [%]
	No EVs		***No EVs***	
	31.3	46.6	19.2	36.2
	Ch-1ph		***Ch-1ph***	
Distr.	**25%**		**25%**	
α	33.8	56.9	21.3	39.7
β	33.8	56.1	21.3	38.8
γ	33.7	56.0	21.2	39.8
AVG	33.8	56.3	21.3	39.4
Distr.	**50%**		**50%**	
α	35.8	67.3	23.2	49.1
β	35.8	68.8	23.3	49.9
γ	35.7	68.3	23.2	48.8
AVG	35.8	68.1	23.2	49.2
Distr.	**75%**		**75%**	
α	38.6	81.0	25.1	61.7
β	38.6	80.1	25.2	62.8
γ	38.7	80.7	25.4	63.9
AVG	38.7	80.9	25.2	62.8
Distr.	**100%**		**100%**	
α	41.4	93.5	27.2	70.5
β	41.0	92.5	27.1	69.7
γ	41.4	94.1	27.3	71.2
AVG	41.3	93.4	27.2	70.4

Table 6.12: Comparison L_{mean} and E_{loss} distributions α, β, γ. Scenario *Ch-1ph*, penetration levels: 25%, 50%, 75%, 100%.

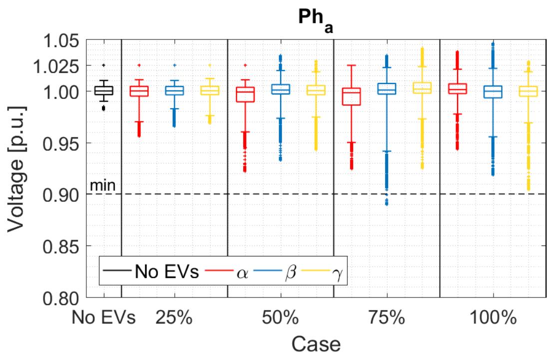
	Losses			
	Tejn		***Rønne***	
	$\mathbf{L_{mean}}$ [%]	$\mathbf{E_{loss}}$ [kWh]	$\mathbf{L_{mean}}$ [%]	$\mathbf{E_{loss}}$ [kWh]
	No EVs		***No EVs***	
	2.29	455	1.90	253
	Ch-1ph		***Ch-1ph***	
Distr.	**25%**		**25%**	
α	2.37	517	1.96	292
β	2.37	517	1.95	289
γ	2.35	510	1.92	284
AVG	2.36	515	1.94	289
Distr.	**50%**		**50%**	
α	2.46	582	2.02	329
β	2.46	581	2.01	330
γ	2.45	577	2.03	334
AVG	2.46	580	2.02	331
Distr.	**75%**		**75%**	
α	2.53	663	2.07	374
β	2.50	656	2.07	376
γ	2.53	668	2.04	376
AVG	2.52	662	2.06	376
Distr.	**100%**		**100%**	
α	2.63	770	2.15	429
β	2.62	759	2.16	432
γ	2.59	753	2.13	427
AVG	2.61	761	2.15	429

Voltage magnitude and unbalance

Figure 6.12, 6.13 and 6.14 shows the voltage magnitude of *phase a*, *Phase b* and *c* respectively. Terminal 4379 in Tejn and terminal 2352 in Rønne are still observed to be the worst for all the considered simulations. In Tejn *phase a* presents under-voltage outliers from 50% EV penetration for all the analyzed distributions. In the same moment, with 100% penetration the voltage is below 0.9 p.u. for more than 5% of the time only in distribution α. In Rønne, the voltage values in distribution β and γ are worse than for α. With 75% penetration, distribution β *phase a* has under-voltage outliers. *Phase c* presents under-voltage outliers as well in distribution γ, but all in all in Rønne the low voltage limitations are never overcome.

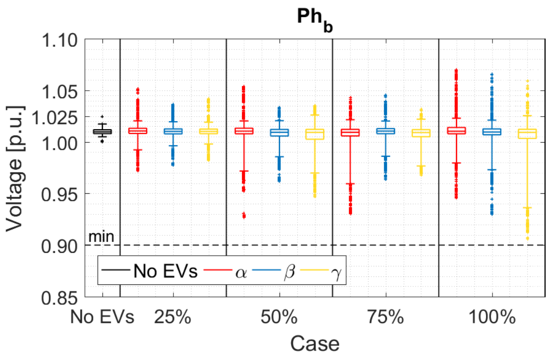


(a) Tejn: 4379

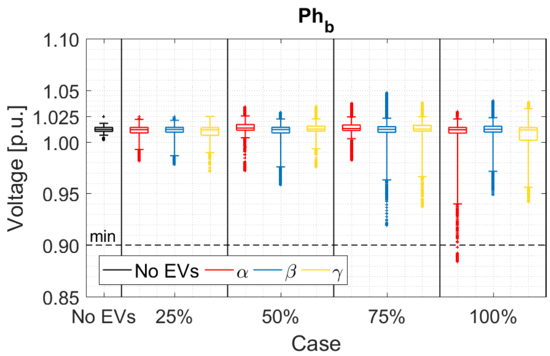


(b) Rønne: 2352

Figure 6.12: Analysis of *phase a*, distributions α, β, γ. Scenario *Ch-1ph*.

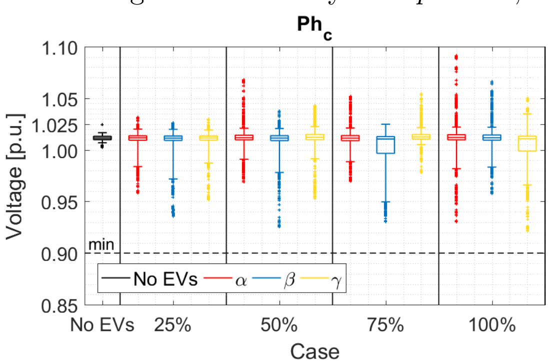


(a) Tejn: 4379

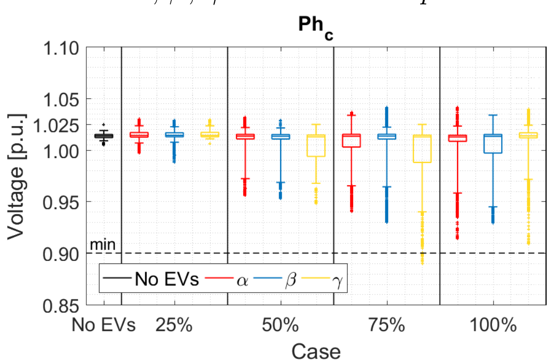


(b) Rønne: 2352

Figure 6.13: Analysis of *phase b*, distributions α, β, γ. Scenario *Ch-1ph*.



(a) Tejn: 4379



(b) Rønne: 2352

Figure 6.14: Analysis of *phase c*, distributions α, β, γ. Scenario *Ch-1ph*.

Due to the effect of the specific charging patterns and distribution of the EVs on the phases, the other end-terminals were analyzed as well. For example terminal 2358 in Rønne behaves similarly to 2352, but in all the analyzed scenarios terminal 2352 is the most critical one.

To sum up, the differences between the three distributions are insignificant, showing that different locations of the EVs, if not too radical, do not influence the congestion and losses. The voltage values in the terminals can be slightly influenced showing under-voltage outliers in various cases, but the only unacceptable case is the 100% EV penetration (α) initially analyzed, in Tejn.

6.6.3 Technical effects of the ToU tariff

DSOs use ToU tariffs to encourage customers to move their consumption from the peak periods to the off peak ones. In this thesis an example of ToU tariff integration is provided to show the impact of the tariffs in a grid with 100% EV penetration. The considered ToU tariffs are the ones applied by Radius to the LV costumers, seen in Section 2.3.2. Since the EVs are considered moveable loads, the following analysis considers the plug-in charging time of all the EVs moved from their respective time at 16, 17, 18, 19 to 20. Even though the higher price of the tariff is applied from 17 to 20, for simplicity also the energy consumed from 16 to 17 is approximated to be moved after 20. From the EV owners' perspective the approximation is reasonable, since they would rarely split the charging time (half from 16 to 17 and the other half after 20) to follow the lower electricity price. It is more realistic to say that if the needed charging time is lower than one hour, the EV owners would still charge between 16 and 17, otherwise they would plug-in at 20. For simplicity this analysis considers all the plug-in charging time at 20. The ToU tariffs can be considered an implicit form of service support provided by the customers, because if they are calculated and applied in the correct way, then the service provided by the users can create benefit for the DSO, avoiding congestion and under-voltage issues. The analyzed scenarios with the ToU tariffs are *Ch-1ph* and *Ch-3ph*. The consumption of the households and the fast chargers are not modified.

Loading and losses analysis

Table 6.13 provides the max transformer loading values and the amount of time the transformer is overloaded during the week. The transformer, in both the grids, is overloaded for more than 9 hours in scenario *Ch-3ph*. In scenario *Ch-1ph* none of the two transformers is overloaded during the week.

Table 6.13: Max transformer loading and overloading time. Scenarios *Ch-1ph*, *Ch-3ph*. Plug-in time: 20.

	Transformer loading			
	Tejn		***Ronne***	
	max [%]	**time** [h]	**max** [%]	**time** [h]
Ch-1ph	93.4	0	73	0
Ch-3ph	201	10.8	162	9.83

Table 6.14: Max cable loading and overloading time. Scenarios *Ch-1ph*, *Ch-3ph*. Plug-in time: 20.

	Cable loading			
	Tejn: St-10058		***Ronne: St-2338***	
	max [%]	**time** [h]	**max** [%]	**time** [h]
Ch-1ph	106	2	85.9	0
Ch-3ph	199	9.75	161	9.82

Table 6.14 quantifies the cable loading. Similarly to the transformer overloading, the most loaded cable in the two grids is overloaded for more than 9 hours in scenario *Ch-3ph*. Furthermore, in Tejn the cable is overloaded for 2 hours also in the scenario with single phase chargers. Even though only one cable per grid is shown in the thesis the overloading of two/three cables per each grid were observed. These cables are displaced in the same feeder after terminals 10058 (Tejn) and 2338 (Rønne) in a row.
Table 6.16 shows the L_{mean} and E_{loss} values for the two grids. With single phase chargers, both the grids have the E_{loss} similar to the initial condition with different plug-in time, as shown in Table 6.15. This is because with plug-in time distributed from 16 to 19, the EVs get to charge concurrently around 18/19, due to the long required charging time. When the plug-in time is at 20, the EVs start to charge all together at 20, but the maximum consumption peak is almost the same as with different plug-in time. On the contrary, when three phase chargers are used, the charging time is shorter, thus when the plug-in time is distributed from 16 to 19 few EVs get to charge concurrently. When all the EVs are forced to plug-in at 20, the amount of EVs charging together is higher, increasing consumption peak, congestion issues and energy losses. The L_{mean} are always in the same range, between 2 and 3%. In Rønne the L_{mean} is increased in scenario *Ch-3ph*, and decreased in the other, due to the fact that the L_{mean} in Rønne are evaluated from 4:00 to 22:00 (as explained in Section 6.3). When Ch-1ph chargers are used, the majority of the EVs are still charging at 22:00, whereas with Ch-3ph chargers most of the EVs are done charging at 22:00, consequently the L_{mean} increases.

Table 6.15: L_{mean} and E_{loss} values for the two study cases. Scenarios *Ch-1ph*, *Ch-3ph*. Plug-in time: 16, 17, 18, 19.

	Losses			
	Tejn		***Rønne***	
	$\mathbf{L_{mean}}$ [%]	$\mathbf{E_{loss}}$ [kWh]	$\mathbf{L_{mean}}$ [%]	$\mathbf{E_{loss}}$ [kWh]
Ch-1ph	2.63	770	2.15	429
Ch-3ph	2.43	692	2.05	432

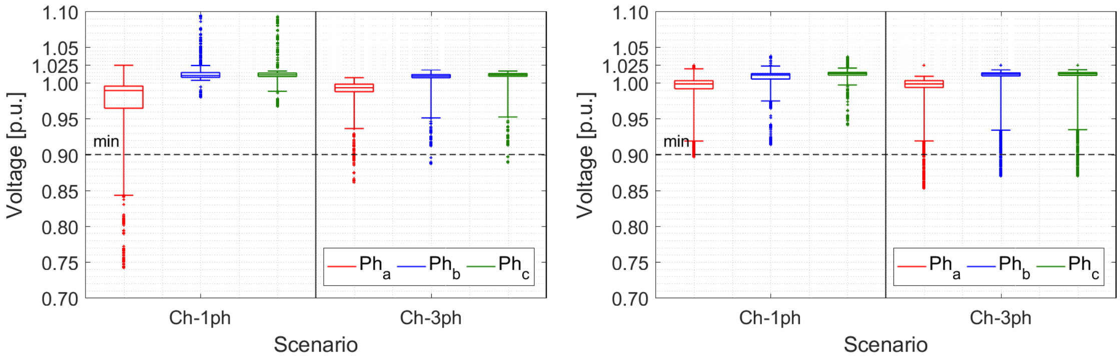
Table 6.16: L_{mean} and E_{loss} values for the two study cases. Scenarios *Ch-1ph*, *Ch-3ph*. Plug-in time: 20.

	Losses			
	Tejn		***Rønne***	
	$\mathbf{L_{mean}}$ [%]	$\mathbf{E_{loss}}$ [kWh]	$\mathbf{L_{mean}}$ [%]	$\mathbf{E_{loss}}$ [kWh]
Ch-1ph	2.63	763	2.05	442
Ch-3ph	2.51	848	2.14	537

Voltage magnitude and unbalance

Figure 6.15a and 6.15b show the voltage of the three phases at the most critical terminals in the two scenarios. Table 6.17 quantifies the amount of time that the voltage is below 0.9 p.u. for the three phases. Both in Tejn and Rønne, under-voltage outliers are observed. Scenario *Ch-3ph* has all three phases with under-voltage outliers, opposite and worsened from the initial situation with plug-in time distributed between 16 and 19. In Rønne the under-voltage is worse with the three-phase chargers than in Tejn, nevertheless all the phases have the 95% of the values above 0.9 p.u..
The analysis shows that the ToU tariffs can generate critical congestion issues with 100% EV penetration. With three-phase chargers, transformers and cables are overloaded for both the grids, whereas with single-phase chargers there is cable overloading only in Tejn. On the contrary, in Tejn the voltage gets unbalanced with the single-phase chargers for a long period of time, whereas with three-phase chargers the grid is more balanced and few

under-voltage outliers are observed.



(a) Tejn: 4379 (b) Rønne: 2352

Figure 6.15: Comparison voltage max, mean and min at the most critical terminals of scenarios *Ch-1ph* and *Ch-3ph* with all EVs plug-in time at 20:00.

Table 6.17: Under- voltage time period during one week (V < 0.9 p.u.) for the two study cases. Comparison scenario *Ch-1ph* and *Ch-3ph* with all EVs plug-in time at 20:00.

	Undervoltage V < 0.90 p.u. time											
	Tejn: 4379						***Rønne: 2352***					
	Ph_a		Ph_b		Ph_c		Ph_a		Ph_b		Ph_c	
	[h]	[%]	[h]	[%]	[h]	[%]	[h]	[%]	[h]	[%]	[h]	[%]
Ch-1ph	18.3	10.89	0	0	0	0	0	0	1.83	1.09	0	0
Ch-3ph	3.84	2.29	1.00	0.60	1.00	0.60	6.20	3.69	3.85	2.29	3.83	2.28

The ToU tariffs is a way to create flexibility on the load consumption. In the short- term, with few EVs the flexible load would be small and it could be a solution to move the consumption from the peak periods. In the long term, with the growth of electricity and high EV penetrations, the flexible load could become high and uncontrollable, causing congestion and under-voltage issues. In Chapter 7 the economic point of view of the EV users will be analyzed and the customers' economic benefit from charging the EVs when the electricity price is lower will be presented.

6.7 Summary

This chapter presented the technical results of the two study cases of Tejn and Rønne considering different EV penetrations and scenarios.
The base case scenario, which represents the current situation without EVs, does not have congestion or under-voltage issues in either the grids.
The analysis of EV penetration with single-phase chargers showed that the 75% level would be acceptable for both grids, without any issues. Higher penetration levels than 25% presented under-voltage outliers in the most critical terminals, but only with 100% EV penetration in Tejn the voltage values were below 0.9 p.u. for more than 5% of the time. With 100% EV penetration, transformer and cables of the two grids were not overloaded with all the EVs charged in single phase, but the power system was unbalanced and the voltage of the three phases were likely to have under-voltage values in the terminals furthest from the transformer station. To deal with under-voltage issues, the EVs were considered

as service providers with the implementation of the active power modulation. The EV support brought some improvements in both the grids. On the other hand, when the three-phase chargers were considered, the systems were more balanced and the voltage of the most critical terminals did not have values below 0.9 p.u.. With three-phase chargers the transformers and the cables were overloaded in Tejn, while the losses decreased thanks to the more balanced distribution of the EV consumption on the three-phases.
With single-phase chargers, the uneven connection of the EVs on the three phases caused the rise of cable overloading, losses and under-voltage issues. The relocation of the EV showed that the EV position is insignificant for the loading of transformer and cables, but it can slightly interfere with the voltage of the terminals. Finally the integration of the ToU tariffs with 100% EV penetration generated overloading problems in the power system. With three-phase chargers both transformers and cables were overloaded, whereas with single-phase chargers the grids were less affected, even though cable overloading and voltage unbalances were observed. In the long-term scenario, the analyzed ToU tariffs would make the load consumption flexible but also uncontrollable. With 100% EV penetration the peak consumption at a certain hour of the day could increase causing congestion issues. In the short-term, with few EVs on the grid, the flexibility of the load consumption created by the ToU tariff, is smaller and more manageable.

7 Economic analysis: assessment of electric vehicle service

This chapter presents the economic investigation based on the technical results analyzed in Chapter 6. The purpose is to provide a method for comparing the suggested EV support service with the traditional DSO approach to grid issues.
Finally the chapter researches the ToU tariffs effects from the economic point of view of the EV users.

Given the growing number of EVs in the market, it is important to analyze plausible solutions to the issues that the EV penetration can generate in the distribution grid. As seen in Chapter 6, the 100% EV penetration with Ch-1ph and Ch-3ph chargers can cause respectively, under-voltage and congestion issues. To deal with these problems, the main idea of the proposed approach is that the EV owners allow the DSO to change the active power consumption of the EVs, in return of an economic remuneration.
As shown in Section 6.4.2, the modulation of active power of the EVs improved the voltage magnitude profile. Nevertheless, the modulation of the active power is mainly used in the case of congestion prevention and loss reduction. Previous studies [7, 12] showed that the EV charging with reactive power is a way of controlling the voltage without affecting the EV charging consumption. Moreover, under-voltage problems are problems of phase unbalances, which can be solved from the DSO in simple ways, in comparison to the congestion issues. Since with single phase chargers transformer and cables were not overloaded, the economic analysis is based on the scenario with 100% EV penetration and three-phase chargers.

This economic study provides an estimate of the value of the EV service, as an alternative method to the upgrading of overloaded components. To the extent of the economic estimate, first a general overview of the current DSO solution is outlined.

7.1 Current DSO solution to solve congestion issues

The current DSO solution to congestion issues is the upgrade of the components. As addressed in Chapter 6, transformer and distribution cables are the most sensitive components to loading problems. Upgrading the transformer consists on replacing the existing transformer by another one with higher rated power. The new transformer has to be established in the same place, and the substation infrastructure adaptation, such as space, ventilation, and connection are in this thesis considered to be the same of the old transformer.
In the economic analysis the power transformers differ from other network components due to the following reasons [76]:

- The capital expenditure (CAPEX) to operation and maintenance costs (O&M) cost ratio is very large
- No significant increase in failure rate with age have been observed until now, since failures tend to be of a random nature, nevertheless the increase of risk failures is classified from 0.5% when the transformer has less than 15 years, to 3% when the transformer has more than 50 years (0.5% is excellent, 2% acceptable, $\geq$ 2% unacceptable) [76].
- There are no established criterion for technical lifetime estimation of the transformers.

Similarly to the transformer, upgrading the cable involves not only the expenses for the new cable, but also the cost of replacement. The new cable needs a higher nominal current, which means higher cable section, nevertheless the main cost comes from the replacement, which increases in urban and semi-urban distribution grid, where underground cables are mainly used.

For the economic quantification of the transformer and cables upgrading, only the CAPEX is considered, since the operating expense (OPEX) are assumed to be the same for the new equipment.

7.2 Economic assessment of DSO-based service from electric vehicles

In this section the EVs service support is considered as different approach to solve the congestion issues. Instead of upgrading the overloaded components, the DSO is considered to be allowed by the EV owners to change the active power consumption when the transformer or the cables are about to be overloaded. This means that the single EV receives less power during the charging time, a part of energy consumption is temporarily delayed and the EV needs more time to be fully charged. Without the EV users' consent this strategy would not be applicable. Therefore an economic benefit for the EV users has to be defined. Based on this basic idea the second economic scenario is designed.
Economic scenario 1 (ES1): the DSO invests today for new upgraded transformer and cables (Section 7.1). Economic scenario 2 (ES2): the DSO waits some years for doing the investment, and in the meantime the EV support service is adopted.

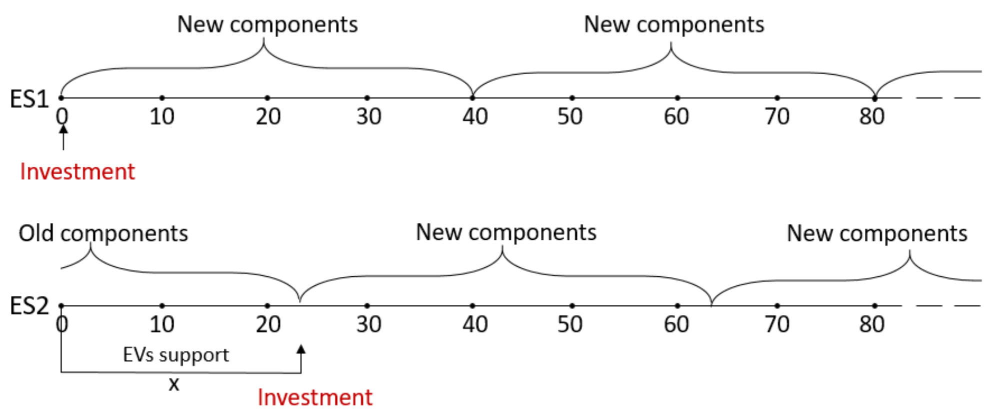


Figure 7.1: ES1 and ES2 framework comparison.

Considering the lifetime of transformer and cables of 40 years [16, 77], the economic scenarios ES1 and ES2 are graphically shown in Figure 7.1.
In ES1 the investment for the new components is made in year 0, whereas in ES2 it is moved forward of x years. x is the remaining lifetime of the component, it depends on the current age of the components in year 0 and for how long they will be able to work. On the long-term the investment delay represents a money saving for the DSO, that can consider to use the money for the EV user's support. The DSO savings are the maximum amount of money that the DSO has at its disposal to payback the EV support service.

Considering the economic lifetime of the new components of 40 years, the money available for the EV support service (M_{EV}) are evaluated as in equation 7.1:

$$M_{EV} = \frac{CAPEX}{40} \cdot x \tag{7.1}$$

Equation 7.1 shows that the considered lifetime determines the available money that the DSO has for paying the EV support. The lifetime of the transformer and cables can usually vary from 30 to 50 years [16, 77], thus with the same CAPEX but a longer lifetime, M_{EV} is lower, decreasing the available money that the DSO can use for the EV support payment. Finally, the investment delay is also an opportunity for the DSO, to determine which are the most appropriate sizes of transformer and cables with the growth of electricity consumption over the years [78].

7.3 Study cases

The two economic scenarios, ES1 and ES2, are here applied to scenario *Ch-3ph* in Tejn. This technical scenario is the only one that showed congestion issues in the technical analysis of Chapter 6 (without considering the sensitivity analysis). For the same scenario, in Rønne, one cable was observed to be overloaded for 11 minutes during one week with maximum loading of 102%. The maximum time of overloading is function of the current that flows in the cable, this analysis does not go into these specific details and the overloading of 11 minutes is assumed not to be a problem. Nevertheless, it is important to notice that, even though this situation is not considered a proper overloading, the cable would be overheated. Consequently the economic analysis is implemented only for the Tejn study case, where the transformer is overloaded for approx. 9.25 h and the cables *St-10058* and *10058-10059* for 2h and 25 min, respectively.

The techno-economic characteristics of the new transformer and cables are shown in Table 7.1 and 7.2 respectively.

Table 7.1: Defined parameters and price of the MV/LV transformer for the proposed grid reinforcement solution. The economic inputs have been obtained from [12, 16].

MV/LV Transformer characteristics			
Technology	3PH	Lifetime	40 years
Rated power	630 kVA	CAPEX	319500 DKK
Nominal frequency	50 Hz	*OPEX input*	
Rated voltage, HV	10 kV	O&M Cost Rate	3.50% of CAPEX/year
Rated voltage, LV	0.4 kV	O&M Cost	11183 DKK/year
Connection	Dyn11	OPEX	11183 DKK/year

Table 7.2: Defined parameters and prices of the cable Al PEX 4x240 mm, for the proposed grid reinforcement solution. The economic inputs have been obtained from [16].

Cable characteristics			
Technology	3PH	Lifetime	40 years
Cross section	240 mm^2	Cost per meter*	653 DKK
Rated voltage	0.4 kV	CAPEX**	69218 DKK
Rated current	400 A (in ground)	*OPEX input*	
Resistance	0.126 ω/km	O&M Cost Rate	3.50% of CAPEX/year
Reactance	0.069 ω/km	O&M Cost	2423 DKK/year
Lenght cable *St-10058* Lenght cable *10058-10059*	50 m 56 m	OPEX	2423 DKK/year

*Cost per meter of the cable, AL PEX 4x240 mm, including material and wages.
**Total CAPEX for the replacement of the two cables *St-10058* and *10058-10059*.

The final investment is 388718 DKK, sum of the CAPEX of transformer and cables.

The overloaded transformer and cables, present in Tejn, are 40 years old. They are still in good conditions and they could be used potentially up to other 10 years, therefore the remaining lifetime x is assumed to be 10 years. In Figure 7.2 the two economic scenarios are compared, with year zero the current one.

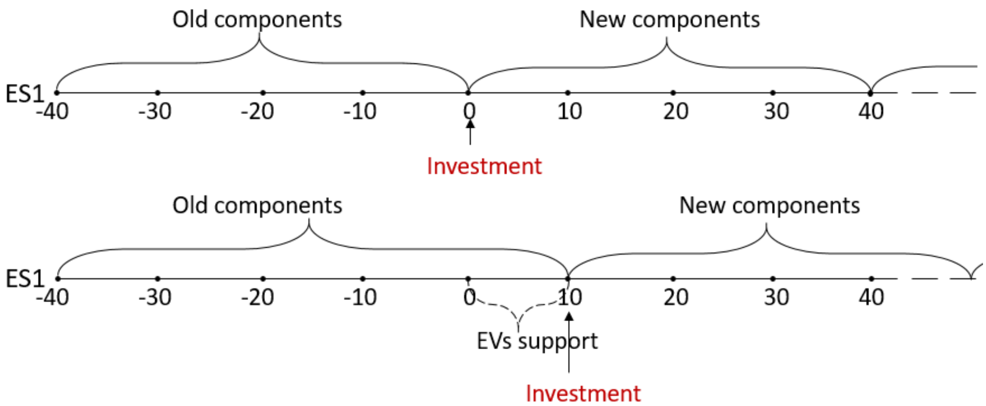


Figure 7.2: ES1 and ES2 framework comparison for Tejn study case.

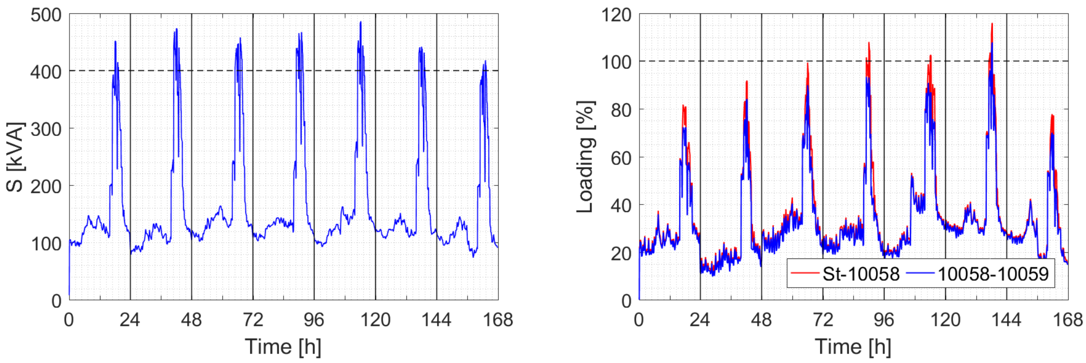
Table 7.3 quantifies the money available for the EV support service for 10 years, one year and one week (considering 52 weeks in one year). The money savings of the DSO in ES2 thanks to the investment delay are evaluated to be 97180 DKK as in equation 7.2:

$$M_{EV} = \frac{CAPEX}{40} \cdot x = \frac{388718\ DKK}{40\ y} \cdot 10\ y = 97180\ DKK \tag{7.2}$$

Table 7.3: ES2: maximum money available for EV support service payment.

ES2	
Money available for 10 years	97180 DKK
Money available per year	9718.0 DKK
Money available per week	186.9 DKK

Considering an equal distribution of the money over the 10 years, the savings per year are 9718 DKK, whereas 186.9 DKK is the maximum amount that the DSO can use for paying back the EV support service per week.
Figure 7.3 illustrates the transformer and cable loading during scenario *Ch-3ph*, Tejn. In Figure 7.3a shows the apparent power at the transformer with the 400 kVA limitation. The consumption above the 400 kVA represents the energy that the DSO has to move to avoid overloading of the transformer. This energy is completely provided by the EVs (neglecting losses of transformer and cables). During the support service the EV consumption is reduced, therefore the total charging time will last longer, until the EVs are charged. Figure 7.3b shows the loading of two cables during the week period. Cable *St-10058* is the connection cable station-terminal 10058 overloaded for 2 hours during the week, whereas cable *10058-10059* links terminals 10058 and 10059 and is overloaded for 25 minutes.



(a) Transformer loading (b) Cable loading: *St-10058* and *10058-10059*

Figure 7.3: Transformer and cable loading during the considered week. Tejn, Scenario: *Ch-3ph*.

The cable overloading is only observed when there is also transformer overloading, whereas the transformer is overloaded for more and longer periods of time. Figure 7.4 shows in detail this situation with the overlap of transformer and cables loading from 12 to 24 on Saturday.

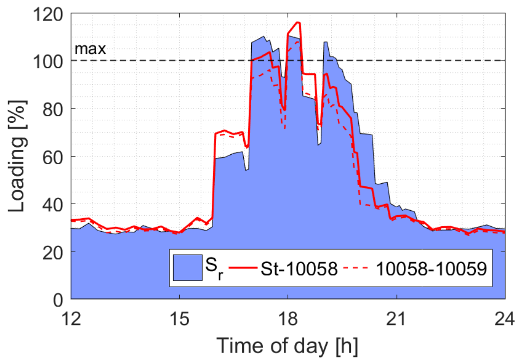


Figure 7.4: Transformer and cable overloading time comparison from 12 to 24 on Saturday.

Because of the coincidence between the overloading of transformer and cables, if the support service is equally distributed between the EVs in the grid, it can be assumed that the moved energy (area between the apparent power of the transformer and the limit line of 400 kVA in Figure 7.3a), also will reduce the loading of the cables.

Table 7.4 firstly quantifies the moved energy during the week, due to the overloading of the transformer. Secondly, considering the potential saving (Table 7.3) and the moved energy per week, the ratio between these two gives the maximum payment per week the DSO can use for the EV support service.

Table 7.4: Moved energy and EV support economic benefit in ES2 scenario *Ch-3ph*, Tejn.

Tejn	
Scenario:	**Ch-3ph**
Moved energy during one week	393 kWh
Maximum payment per kWh	0.48 DKK/kWh

Less energy is required to be moved during one week, higher is the amount of money that can be used by the DSO to pay per kWh of moved energy. From the EV users' perspective, this means that the EV support is paid less DKK/kWh when more support is provided. Considering an equal distribution of the moved energy between the 127 EV users, the moved energy per EV owner is 3.09 kWh/week. Thus the savings for an average EV user[1] are found to be 1.48 DKK per week, and 77.0 DKK for the entire year, considering the 52 weeks equal to the one analyzed. From the point of view of the DSO, the EV support in ES2 is used as another solution to the upgrade of the components (ES1). The new components represent an investment for the DSO, therefore when spending an amount of money on buying new components, the DSO wants to be sure that the investment is more preferable than other options. In this scenario the transformer is overloaded every day of the week, but it has to be noticed that the household consumption during the year is not always high as during this week. As analyzed in Chapter 4, during the considered week 9 the household consumption is higher than the one in week 7 due to the electric heating. Moreover, in Denmark the domestic electricity consumption is higher in winter than in summer, but the grid, must be dimensioned for the winter peak. Considering a scenario with few periods of overloading of the components, the EV support becomes much more significant for the DSO, which prefers to pay the EV service than to buy new transformer and/or cables. In this case, the DSO could buy the EV support service for few months in a year and pay more DKK/kWh for the EV support service. For example, since the electricity consumption during summer is lower and it is not expected to cause congestion, instead of buying the EV service during the all year, the DSO could buy the service only for three winter months. In this case the DSO would have more money for the EV support payment and the EV users would be more motivated to accept the deal. The new situation is summarized in Table 7.5:

[1]This approximation is made to give an average value of payment per customer, even though the EVs charging patterns are different and there would be some EV users earning more and some less.

Table 7.5: ES2: EV support service for three months per year.

ES2	
Money available for 10 years	97180 DKK
Money available per 3 months (12 weeks)	9718.0 DKK
Money available per week	810 DKK
Moved energy during one week	393 kWh
Maximum payment per kWh	2.06 DKK/kWh

The maximum payment per kWh would be 2.06 DKK/kWh, four times larger than the previous one, it could give more motivation to the EV users to sell the service. The remuneration for an average EV user would be the same as the previous case (77.0 DKK), because the available amount of money is the same, and it would only be differently distributed over the year.
The domestic electricity price in Denmark is approx. 2.31 DKK/kWh, in the first case the EV users could receive a remuneration or price reduction of the 21% of the electricity cost, whereas with three months of EV support the 90% of the price could be remunerated/reduced.

The analysis has not been applied to Rønne, since the transformer is not overloaded during the week, in any of the technical scenarios. Even though the components do not need to be upgraded, in scenario *Ch-3ph* the transformer is very close to be overloaded, with 99.5% of maximum loading, and cable *St-10058* is "overloaded" for 11 minutes (not considered properly overloading but more overheating). This situation is similar to the last case analyzed in Tejn with 3 months of EV support. Indeed if the components would get overloaded for few times, for the DSO it would be more cost effective to buy the EV support service than buying new transformer/cables.

Finally, the investment delay is an opportunity for the DSO to determine the most appropriate size of transformer and cables with the growing electricity consumption after the 10 years. For example if the EV support service is proved to be a good solution for the DSO, power system and users, after 10 years the DSO could decide to buy a new transformer of 400 kVA and to change the cables with other of same characteristics (necessary since the components are already 40 years old). Since the main cost of new cables comes from the replacement, the cost of the new cables can be considered the same. The difference between the investment of the upgraded transformer (630 kVA) and the investment without upgrading (400 kVA transformer) could be used for the payment of the EV support service.

Table 7.6: Defined parameters and prices of the 400 kVA MV/LV transformer. The economic inputs have been obtained from [12, 16].

MV/LV Transformer characteristics			
Technology	3PH	Lifetime	40 years
Rated power	400 kVA	CAPEX	202857 DKK
Nominal frequency	50 Hz	*OPEX input*	
Rated voltage, HV	10 kV	O&M Cost Rate	3.50% of CAPEX/year
Rated voltage, LV	0.4 kV	O&M Cost	7100 DKK/year
Connection	Dyn11	OPEX	7100 DKK/year

In Table 7.6 the technical and economic characteristics of a 400 kVA transformer are provided, and doing the difference between the CAPEX of the two transformers, the DSO savings are evaluated to be 116643 DKK, money available for the EV support service.

7.4 Economic effects of the Time of Use tariff

As investigated in Section 6.6.3, the ToU tariffs (the ones used by Radius) applied to a grid with 100% EV penetration generate a critical effect on the power system, mainly as congestion issue.
The ToU tariffs generate flexibility on the load consumption and in implicit way the EVs could give service support to the power system. In this case the EV users do not receive a remuneration or reduced costs from the DSO, since they are not obliged to change their EV active power consumption. They are instead incentivized by the possibility of saving some money, moving their electricity consumption over time.
In this section the economic point of view of the EV users is analyzed. In Table 7.7 the moved energy, from 16-20 after 20 during the whole week, is provided. The energy moved is higher in Tejn than in Rønne, because in Tejn there are more EVs. Moreover, the charging patterns are differently distributed over time, for example the vehicles that plug-in at 17:00 in Tejn can have different charging pattern than the ones that plug-in at 17:00 in Rønne, causing a different amount of energy moved. These values are used to evaluate the savings of the EV users, due to the movement of the electricity consumption after 20:00. 0.5 DKK is the saved amount of money per kWh for the considered ToU tariffs, as described in Section 2.3.2.

Table 7.7: Energy moved and savings for scenarios *Ch-1ph* and *Ch-3ph*, with the considered ToU tariffs.

	Tejn		***Rønne***	
Number of EVs	127		110	
Scenario	*Ch-1ph*	*Ch-3ph*	*Ch-1ph*	*Ch-3ph*
Energy moved from 16-20 after 20 in 1 week [kWh]	2987	5286	2686	4869
EV users total saving 1 week [DKK]	1489	2643	1343	2435
Average saving per customer in 1 week [DKK]	11.73	20.81	12.21	22.13
Average saving per customer in 1 year [DKK]	305.0	541.1	317.5	575.4

The combined saving for the EV users is higher when using three phase chargers than single phase chargers. Even though the EVs are charging in very different ways[2], the average saving per customer is here determined considering an equal distribution of the moved energy and consumption between the 127 EVs in Tejn and 110 EVs in Rønne. This approx. shows that the average saving, for both the analyzed study cases, are circa 12 DKK/week in *Ch-1ph* scenario and 22 DKK/week in *Ch-3ph* scenario.

[2]This approximation is made to give an average value of saving per customer, even though the EVs charging patterns are different (as seen in Chapter 3), and there would be some EV users saving more and some less.

During a one year period, the savings for an average EV user is evaluated considering 26 weeks, since the ToU tariffs by Radius is implemented for 183 days/year (Section 2.3.2).

Comparing the EV support service in Section 7.3 with the ToU tariffs, the economic benefit of the EV users is much higher with the ToU tariffs. On the contrary the impact of the ToU tariffs implementation on the power system and the DSO would be technically unrealistic, as analyzed in Section 6.6.3. In addition, the results of scenario ES2 were depending on the characteristic of the considered week multiplied per 52 weeks (1 year). This was observed to be a bad case scenario, when knowing that during the year the household electricity consumption changes. Differently, when considering the ToU tariffs, willing to save money the EV owners would move their consumption after 20:00, increasing the possibility of generating congestion, even when the normal distribution of the EVs from 16 to 19 would not be a problem.

7.5 Summary

In this chapter the economic analysis has been developed. The upgrading of the components, as current DSO solution to congestion issues was firstly presented. The economic analysis was applied only to Tejn, since in Rønne the congestion issues were not critical to require the upgrade of the components. The economic scenarios were before compared as general investigation and then applied to the technical scenario *Ch-3ph* in Tejn. The EVs were investigated as support service for the power system and DSO, and economic remuneration for the EV users. It was found that the EV support service could be paid maximum 0.48 DKK/kWh, meaning that an average customer could earn in a year circa 77.0 DKK. Furthermore, it was shown that with long periods of overloading, the DSO prefers to buy new components than the EV support service. On the contrary, if the components are overloaded for few periods of time, it is more cost-effective for the DSO to buy the EV support service. Since the EV support would not be needed for most of the time, the DSO could buy the service for a shorter period, like three months. In this case the DSO can pay the EV support more money per kWh and the EV users are more motivated to sell their support.
In Denmark the domestic electricity consumption is higher in winter than in summer, but the grid, in this case Tejn, must be dimensioned for the winter peak, which gives significantly higher value to the EVs as flexible load during the winter period.
Finally the economic value of the ToU tariff, as implicit form of EV service support, was investigated from the point of view of the EV users. It was shown that the average saving per customer could be approx. 310 DKK per year with single-phase chargers and 550 DKK per year with three phase chargers.

8 Conclusion and future work

This thesis focused on assessing the effects of the potential EV penetration on LV distribution grids. The subject was approached technically and economically. First, a model to design realistic and differentiated EV charging patterns was created. Second, two LV grids, Tejn and Rønne, representative distribution grids of the Danish island of Bornholm, were modelled and analyzed. Third, the effect of the EV penetration, with different levels and rated charging powers, was investigated in the two study cases, determining congestion and under-voltage issues. Finally, the possibility to use the EVs as a service support was studied, deriving economic values for the provided service for the power system, aggregator and user. The topics just summarized are listed in four research questions in Section 1.3. This chapter aims to conclude them, relying on results and knowledge obtained.

- **How can EVs charging pattern be simulated based on the national travel survey?**
  The Danish national travel survey gives information about the driving behaviour of car users, including the average kilometres driven by the cars in Denmark and in Bornholm. Based on this information, the implemented model generates individual charging patterns for the EVs, simulating the distribution characteristics of the known statistical data. Firstly, the EVs were divided in groups per average distance driven per day. A large study done by Nissan, determined the probability of charging the EV depending on the SOC and the daily driven distance. The model generated individual EV charging patterns, which as a group fit the distribution of driving distance and time in Denmark, and the plug-in ratio in Japan. Thanks to the National travel survey, the plug-in time of the EVs was split into four, 25% EVs per each plug-in time: 16, 17, 18, 19. The charging time was determined on account of the characteristics of the considered Nissan LEAF 40 kWh, single- three- phase chargers and SOC at the end of the day. The output of the model is the charging pattern of each EV.
  It was found that because most of the EVs does not need to charge every day, the simultaneous charging with single-phase chargers is never more than 40-45% EVs. Additionally, when using three-phase chargers the charging power is tripled, but the combined peak only increases with 50%, because the simultaneous charging is reduced to 20-25%.
- **What are the impacts of different penetration levels of EVs on the distribution network of Bornholm?**
  The charging patterns were randomly distributed as EVs of the households of the two LV grids. With single phase chargers the considered penetration levels were 25%, 50%, 75% and 100%. 100% penetration means that every household has an EV. The investigation of the different penetration levels pointed out a linear increase of the transformer and cable loading with the increment of the EV penetration. On the

contrary, a similar linearity could not be observed for the voltage behaviour. The phase-to-neutral voltage magnitude was much more dependent on the location of the EVs on the phases. The initial condition of the grids, without EVs, was found to be already unbalanced, with 40% of load in phase a, 30% in phase b and 30% in phase c. Alternatively, the EVs were equally distributed on the three phases, but the single phase connection and the differences between the charging patterns still generated unbalances in the most critical terminals, loading one phase more than the others. The voltage unbalance was observed mainly in Tejn. Considering 100% as the maximum loading, transformer and cables were not overloaded with any of the penetration levels, whereas the voltage analysis showed under-voltage values below 0.9 p.u. in the most critical terminals from 50% EV penetration in Tejn and 100% EV penetration in Rønne. Nevertheless, considering the EU standard, only the 100% EV penetration in Tejn had under-voltage in more than 5% of the time, the others were still within the limits.
The investigation of the EVs connected with three-phases showed that with 100% EV penetration, congestion issues of transformer and cables can occur. Differently, the power system would be more balanced than with EVs connected in single-phase, no under-voltage issues were observed and the losses of the grids were decreased.
The impact of single-phase chargers, with uneven distribution on the three phases was analyzed implementing an unbalanced case with: 50% EVs in phase a, 25% in phase b and 25% in phase c. The unbalanced case increased the distribution losses and voltage unbalances caused by the uneven phase loading. The sensitivity of the specific location of the charging patterns in the grid was also investigated. The diversified EVs, initially placed on the grid in a random way, were relocated with two more simulations for each penetration level. It was found that the position of the EVs does not interfere with the congestion issues, and the most critical terminal does not change. Nevertheless, the specific location of the EVs can interfere with the voltage magnitude of the most critical terminals, but not in a critical way.
It was concluded that, in the short term with few EVs, the DSO should mainly focus on balancing the grid. On the contrary, in the long term, the growing electricity consumption together with high EV penetrations, could generate congestion issues as main problem in power systems.

- **Which value can the EVs, as a flexible active component of the distribution system network, create for the system? How should it be remunerated?**
  The EVs can be used as active components of the power system, with the active power modulation described in Section 5.5.1. The active power modulation was implemented in the scenario with 100% EV penetration and single-phase chargers for the two study cases. Using the active power control, the voltage magnitude at the most critical terminals was improved. Nevertheless, the modulation of the active power is mainly used in the case of congestion prevention and loss reduction, because the under-voltage problems can be solved by making the grid more balanced.
  With the implementation of the three phase chargers, the 100% EV penetration caused congestion issues in Tejn, grid with highest initial household consumption. The current DSOs solution to congestion issues is the upgrade of the components. In this thesis a different approach was based on the EV support service, considering

that the EV owners allow the DSO to change the active power consumption of their EVs, in return of an economic remuneration. The EV service repayment was derived as investment delay of the DSO for the upgrading of the components. Based on the economic value of the replacement of transformer and some cables, the potential payment for the EV support was evaluated to be of 187 DKK/week, value that depends on components age and remaining life. To avoid the transformer and cable overloading, a certain amount of energy had to be moved by the DSO. Based on this energy, 0.48 DKK was the maximum repayment per kWh, whereas the average service estimated value was 77 DKK/year per each customer, avoiding grid reinforcement. It was concluded that, if the components are overloaded for more and long time periods, for the DSO it is more cost effective to buy new components than the EV support service. The electricity consumption in Denmark is higher in winter than summer, thus the components are not expected to be overloaded for most of the months. Nevertheless, the grid must be dimentioned for the worst peak. For this reason the DSO could buy the EV support service for few months, the potential payment for the EV support would be higher and the EV users would be more motivated on selling the service. With few and short overloading periods, for the DSO the EV support service is much more cost-effective than buying new components.

- **How could taxes/tariffs or regulations be used to incentivize the smart integration?** The investigation of the ToU tariffs showed that the effects of these tariffs depend on various and uncontrollable factors. Today it is still difficult to determine a share of customers or consumption that would always be moved from the peak to the off peak period. Considering the loads split in moveable and non moveable loads, the EVs are part of the first group, as flexible active components of the distribution system network. A type of ToU tariffs was analyzed and tested in the 100% EV penetration scenarios. Moving the plug-in time of all the EVs to 20, the 100% EV penetration generated congestion and under-voltage issues for the analyzed scenarios. With single phase chargers, only one cable was overloaded, whereas with three phase chargers the congestion issues were significantly worse. Not only congestion, but also under-voltage issues were observed. On the contrary, the average EV users were observed to save from 310 DKK to 550 DKK as average yearly value, depending on the considered chargers.
  In a growing electricity consumption and EV penetration, the analyzed ToU tariffs could make the load flexible but also uncontrollable, causing congestion issues in the power system. In the short-term, with few EVs, the flexibility introduced by the ToU tariff is smaller, and the problems that could rise in the power system would be more moderated and manageable.

Perspectives

As presented in the introduction chapter a higher penetration of EVs in the car fleet is desired in order to reduce CO_2 emissions. In relation to this, the current study provides usable knowledge and insight on the requirements of the power system and can be beneficial for DSOs like BEOF, in relation to their long-term planning of the electricity grid.
A direct comparison of the EV penetration analysis with previous studies is difficult, due to the low amount of studies in the topic. However, in relation to the study of another Danish LV grid in the town of Borup [12], which showed congestion and under-voltage issues with

35-37% EV penetration, it should be noticed that the implementation of more realistic charging pattern for the EVs in Bornholm gave better results. Indeed with single-phase chargers both the grids did not present congestion issues up to 100% EV penetration, and only the most loaded grid had under-voltage problems with 100% penetration.
Even though most of the technical results did not present overloading of transformer and cables, it is worth mentioning that nowadays some grids are operated with maximum power consumption 70% of the capacity limit, the rest 30% is the reserved safety capacity band [78]. The 70% value is not a general limit, it can be lower or higher depending on the feeder characteristics. This is done to preserve the emergency reliability of the power system, even though the growing consumption from traditional and new appliances, such us EVs. In emergency situations, transformer and cables of a feeder could have to provide power to customers of other feeders, using the rest 30% of their capacity. Considering a lower limit for the maximum power consumption of transformer and cables, most of the analyzed scenarios would present congestion issues, opening research questions for future work.

8.1 Future work

This section aims to outline some possible topics for further research that have not been covered in this thesis:

- The plug-in rate at workplace were not included in the charging pattern model. The consideration of the workplace chargers could bring to light a more distributed consumption of electricity from EVs during the day time, decreasing the unbalances and congestion issues in the different scenarios.
- The simulations were conducted for a single EV model with 40 kWh of battery capacity. Due to the different technical characteristics and charging behaviors, it is interesting to consider the combination of different EV models in the proposed investigations. Moreover, the implementation of larger EV batteries is expected to decrease the amount of charging, decreasing as well the problems in the grid.
- The reactive power control was not considered in the power modulation of the EVs with single phase chargers. Unlike the active power, the reactive power is a local voltage support that does not affect the EV charging pattern. Even though the reactive power control is still not implemented, when the voltage in the most critical buses has under-voltage values for long periods of time, the reactive power approach is more interesting to investigate, technically and economically.
- Most of the technical results did not present overloading of transformer and cables with 100% loading limitation. Nevertheless, today some grids are operated with lower maximum power consumption, to preserve emergency reliability of the power system. The grids with different EV penetrations could be analyzed to determine the limit band of reliability in the different scenarios.
- The technical analyses showed the rise of congestion and under-voltage issues when ToU tariffs is used in grids with 100% EV penetration. This topic could be of particular value to evaluate the optimal relationship between EV penetration and ToU tariff without causing issues in the future grids. Thanks to the smart meters, more precise data will be available in the near future, making these analyses more attractive and achievable.

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A Modelling theory and derivations

A.1 Modelling unbalanced three-phase electrical power system

The method of symmetrical components is a powerful mathematical method for representing unbalanced poly-phase systems into decomposed sets of phasors. With this method, an unbalanced three-phase electrical power system can be represented by three symmetrical phasors:

- Positive sequence components: three phasors with equal magnitudes, but phase displacement of $\pm 120^o$ and positive sequence.
- Negative sequence components: three phasors with equal magnitudes, phase displacement of $\pm 120^o$ and negative sequence
- Zero sequence components: three phasors with equal magnitudes, zero phase displacement

The graphical representation of the three sets of sequence components for the phase voltages are observed in Figure A.1.

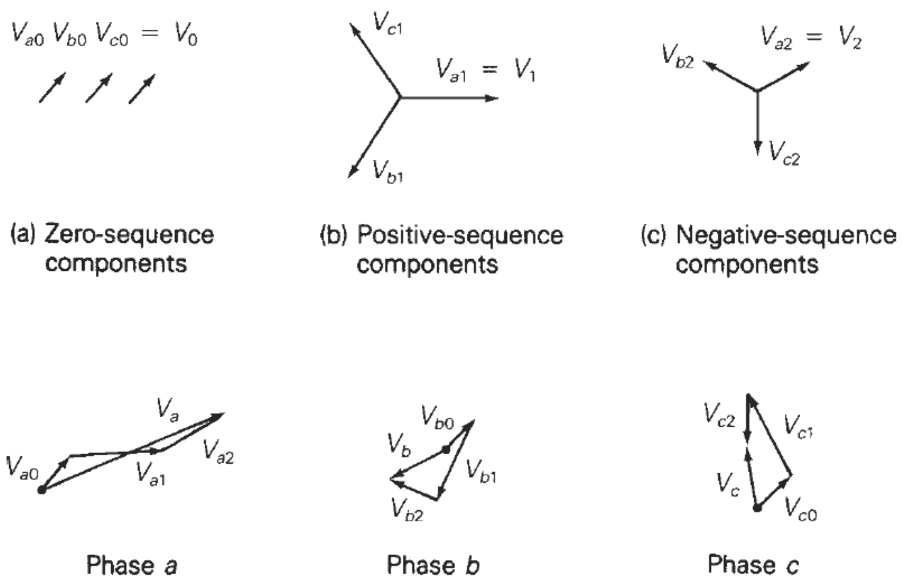


Figure A.1: Graphical representation of the three sets of sequence components for the phase voltages [11].

The relation between the symmetrical and asymmetrical system is defined as:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_+ \\ V_- \end{bmatrix} \tag{A.1}$$

considering V_a, V_b, V_c the phase-to-phase voltage phasors and V_0, V_+, V_- the zero, positive and negative sequence components. α is the rotation operator: $\alpha = e^{j120\,\mathrm{deg}}$ Finally the zero, positive and negative set can be derived as:

$$\begin{bmatrix} V_0 \\ V_+ \\ V_- \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{A.2}$$

Considering a three-phase line with neutral conductor, the self- and mutual impedance of the phase conductors are calculated as follows:

$$Z_S = \frac{1}{3} \cdot (Z_0 + 2 \cdot Z_1) \tag{A.3}$$

$$Z_m = \frac{1}{3} \cdot (Z_0 - Z_1) \tag{A.4}$$

with Z_0 and Z_1 the zero and positive sequence impedances, respectively. For more information read the PowerFactory manual [73].

A.2 Active power modulation: theory

Distribution grids, as the ones considered in Figure 4.3 and 4.4 can be summarized as in Figure A.2.

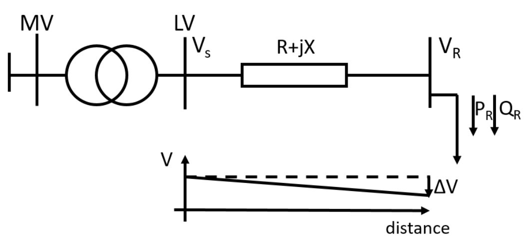


Figure A.2: Relationship between P, Q and V in LV distribution grids. Adapted from [7].

The voltage drop across the feeder is expressed as follows:

$$\begin{aligned} \Delta V &= V_S - V_R && \text{(A.5)} \\ &= (R + jX)I && \text{(A.6)} \\ &= (R + jX)\left(\frac{S_R}{V_R}\right)^* && \text{(A.7)} \\ &= (R + jX)\frac{(P_R + jQ_R)^*}{V_R^*} && \text{(A.8)} \\ &= \frac{RP_R + XQ_R}{V_R^*} + j\frac{XP_R - RQ_R}{V_R^*} && \text{(A.9)} \end{aligned}$$

V_S stays for sending bus voltage, V_R for receiving bus voltage, R and X are the cable resistance and reactance.

Controlling P and Q injected to or consumed from the grid, voltage quality issues can be solved. In the present study cases, P_R and Q_R can be written as in equation A.10 and A.11:

$$P_R = P_R^{PV} - P_R^L - P_R^{EV} \quad (A.10) \qquad Q_R = Q_R^{PV} - Q_R^L - Q_R^{EV} \quad (A.11)$$

with:

- P_R^{PV} and Q_R^{PV} active and reactive power injected by the PV panels to the grid (where present);
- P_R^L and Q_R^L active and reactive power consumed by the householders from the grid;
- P_R^{EV} and Q_R^{EV} active and reactive power consumed by the EVs from the grid. Q_R^{EV} is always equal to zero in this analyses.

Since the angle between the nodes is small, in equation A.9 the imaginary part can be disregarded and the voltage drop is rewritten as in equation A.12, showing that the voltage ΔV is directly proportional to the EV active power consumption:

$$\Delta V = \frac{R(P_R^{PV} - P_R^L - P_R^{EV}) + X(Q_R^{PV} - Q_R^L)}{V_R^*} \quad (A.12)$$

A.3 Derivation of the power flow equations

The power flow equations, active and reactive power, of a simple line as the one shown in Figure A.3 are written as in equation A.13 and A.14:

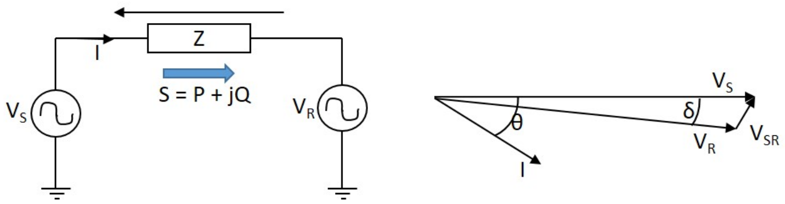


Figure A.3: Equivalent circuit and phasor diagram of a line. Adapted from [12].

$$P = \frac{V_S[V_S - V_R\cos\delta]\cos\theta + V_S V_R \sin\delta\sin\theta}{Z} \quad (A.13)$$

$$Q = \frac{V_S[V_S - V_R\cos\delta]\sin\theta + V_S V_R \sin\delta\cos\theta}{Z} \quad (A.14)$$

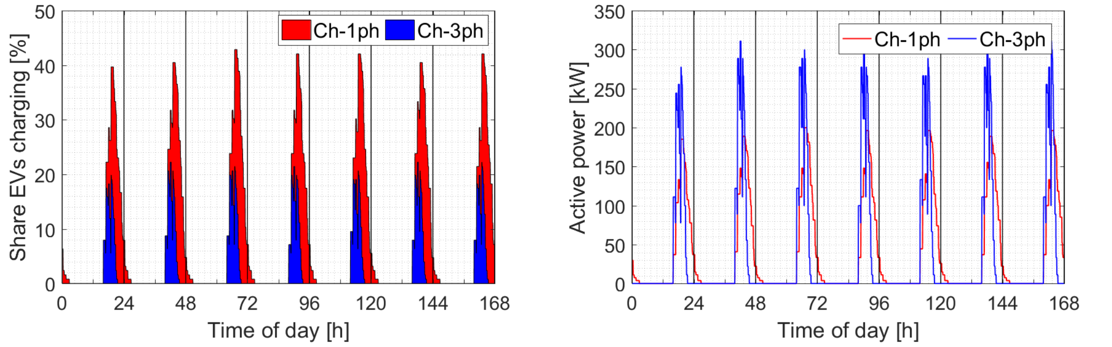
Taking into consideration LV lines, the reactive component is usually larger than the inductive one ($R >> X$), thus the impedance angle θ is approximated to 0 and δ is small. In this view the following approximations can be done: $\cos\delta = 1$ and $\sin\delta = \delta$, meaning that expressions A.17 and A.18 can be derived as follows:

$$P = \frac{V_S[V_S - V_R]}{R} \quad (A.15) \qquad Q = -\frac{V_R V_S}{R} \quad (A.16)$$

From equation A.15 and A.16, equation A.17 and A.18 are derived:

$$V_S - V_R = \frac{RP}{V_S} \quad (A.17) \qquad \delta = -\frac{QR}{V_R V_S} \quad (A.18)$$

B Additional technical results



(a) Percentage EVs charging. (b) Sum active power consumption of the EVs.

Figure B.1: Charging patterns comparison conducted scenarios, one-week period, Tejn.

Table B.1: Comparison mean and max cable loading, cases α, β, γ. Scenario *Ch-1ph*: 25%, 50%, 75%, 100%.

	Cable loading			
	St-10058		***St-2338***	
	mean [%]	**max** [%]	**mean** [%]	**max** [%]
	No EVs		***No EVs***	
	26.9	51.6	19.5	38.5
	Ch-1ph		***Ch-1ph***	
Distr.	**25%**		**25%**	
α	29.3	55.4	21.8	48.0
β	29.9	53.2	21.0	45.2
γ	29.5	57.3	21.6	43.1
AVG	29.6	55.3	21.5	45.4
Distr.	**50%**		**50%**	
α	29.6	57.3	24.6	63.6
β	30.6	60.3	25.1	59.7
γ	29.6	57.4	25.1	59.9
AVG	29.9	58.3	24.9	61.1
Distr.	**75%**		**75%**	
α	34.1	74.4	27.3	68.7
β	35.8	84.6	25.8	71.3
γ	33.7	77.2	26.9	72.2
AVG	34.5	78.7	26.7	70.7
Distr.	**100%**		**100%**	
α	36.0	91.6	27.4	79.6
β	36.1	86.0	27.4	76.6
γ	35.9	87.1	27.8	79.4
AVG	36.0	88.2	27.5	78.5

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