Deliverable D4.3 – B2

Grid Impact studies of electric vehicles

Reinforcement Costs in Low-voltage Grids

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1 Executive Summary

The scope of this report is to describe the impact of EVs on the reinforcement and reinforcement costs of low-voltage networks. The focus is on how different parameters relating the EVs to the grid affect the reinforcement costs. The evaluation has been done by developing and analyzing a set of scenarios that vary the parameters under study. These parameters are:

- Charging Power
- Charging Profile
- EV Location
- EV Penetration

Apart from these parameters, the influence of voltage control has also been evaluated.

Load flow simulations have been performed on each scenario using ITRES. ITRES is a tool developed within Green eMotion[1] that evaluates reinforcement costs over a number of years with a user-specified load increase. The reinforcement schedule and reinforcement cost results have been analyzed and comparisons have been made for each of the parameters in the study. The comparison of costs is based on net present value (a way of representing time value of money concept). This assures that it is not only the amount of reinforcement that is considered, but also the time at which it occurs.

The results have shown that the charging profile is the most important parameter of all the investigated parameters. As the charging profile depends on the charge management strategy, it means that the charge management strategy is the most important parameter. With a grid friendly charge management strategy it is possible to avoid most reinforcements and their associated costs, reducing the significance of all the other parameters.

The results also showed that a simple timer based charge management strategy with the goal of improved grid friendliness, could end up making the charging process

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[1] D4.3-C1 “Tool Kit” will be published early 2014

less grid friendly due to a kickback effect. This resulted in significantly increased reinforcement costs in many of the networks when using the simple timer based charge management strategy. More elaborate timer based charge management strategies can likely avoid kickback and its negative effects on reinforcement costs, while still providing the benefits of moving EV charging away from the existing load peaks.

Variations in EV penetration and charging power had a significant impact on reinforcement costs, showing the importance of accurate forecasting.

EV location and voltage control only had an economic impact in networks where reinforcement was necessary due to voltage issues. Location had a significant impact on reinforcement costs and showed that in order to evaluate the reinforcement of a network, it is necessary to know the exact location of EVs during grid planning. The use of voltage control could defer the vast majority of reinforcements associated with voltage issues and allow long feeders to accommodate a significantly larger amount of EVs before reinforcement is necessary.

It was found that new tools are needed – tools that can estimate the economic impact of different solutions better and allow more flexibility when it comes to load forecasting. It was also found that new methods may be necessary for estimating load, especially in cases with fewer customers and flexible loads, where averages are a poor estimation. New technologies such as Smart Meters can provide a large statistical base which can facilitate more accurate load estimation and forecasting.

2 Introduction

Europe is undergoing a change from fossil based energy consumption to renewable energy sources such as wind, water, solar energy, burning of waste and bio products. A great part of this development has taken place in the electricity market, replacing the existing power production units with something more environment friendly, thus reducing CO2 emissions and lowering the dependency on heavy fuel oil products. As part of a similar transition in the transportation sector, electric vehicles have long been in use as trams and trains. To fulfill the Transport 2050[2] goals, which include a drastic reduction of CO2 emissions from the transport sector, new technology is needed and for the common car the electric car is the primary replacement.

2.1 Electric Vehicles for Personal Transportation

The transition from oil based cars to electric cars (EVs) will have a significant and positive effect on society, the local environment in particular, and set new demands to the electric grid.

Unlike Internal Combustion Engine cars (ICE), EVs are connected to and use the electric grid when refueling, either via an On-board charger or via an Off-board charger.

Chargers are typically connected to the low-voltage grid. Home chargers are usually single phase units, while public fast chargers are three phase units with a much higher power rating. Home chargers are expected to be the primary charging point for EVs and are located in residential low-voltage grids. Fast chargers are expected to be employed in different parts of the low-voltage grid.

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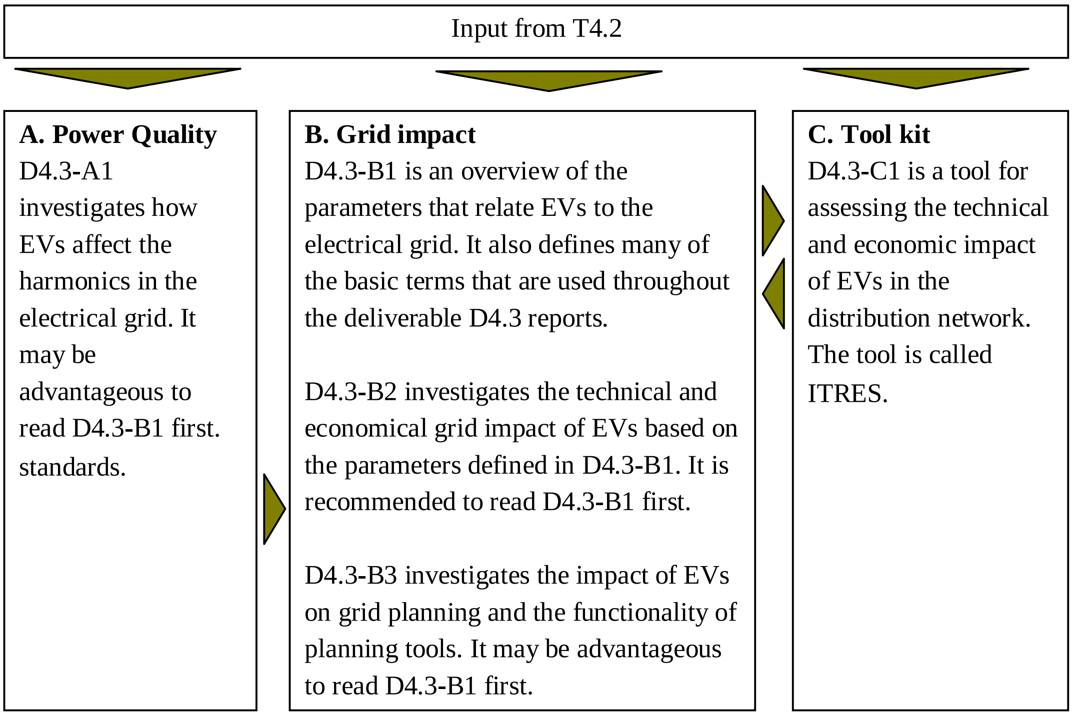
[2] Goals for the future in the transportation sector, details can be seen at: http://europa.eu/rapid/pressReleasesAction.do?reference=IP/11/372&format=HTML&

2.1.1 EU Project Green eMotion and D4.3

The large EU project Green eMotion focuses on electric vehicles; the technical development, penetration, and interaction with society. The project consists of eleven work packages investigating numerous topics related to EVs. The project is supported by partners throughout the European continent and each investigation stands as a small part of a larger picture.

D4.3 will include recommendations for future planning tools for DSOs and an investigation of the effect EVs have on the grid and power quality. D4.3 consists of several reports covering different topics relating EVs to the electrical grid. An overview of D4.3 is shown in Figure 2.1.1.



Input from T4.2

A. Power Quality
D4.3-A1 investigates how EVs affect the harmonics in the electrical grid. It may be advantageous to read D4.3-B1 first. standards.

B. Grid impact
D4.3-B1 is an overview of the parameters that relate EVs to the electrical grid. It also defines many of the basic terms that are used throughout the deliverable D4.3 reports.

D4.3-B2 investigates the technical and economical grid impact of EVs based on the parameters defined in D4.3-B1. It is recommended to read D4.3-B1 first.

D4.3-B3 investigates the impact of EVs on grid planning and the functionality of planning tools. It may be advantageous to read D4.3-B1 first.

C. Tool kit
D4.3-C1 is a tool for assessing the technical and economic impact of EVs in the distribution network. The tool is called ITRES.

Figure 2.1.1: Overview of deliverable D4.3.

All reports are available on the Green Emotion website under following link: http://www.greenemotion-project.eu/dissemination/deliverables-infrastructure-solutions.php

2.1.2 The Subject for the Investigation

This study aims to investigate the economic impact on grid reinforcements arising from the introduction of EVs. GeM WP9 is going to investigate the economic impact on a European scale. This study looks to investigate the economic impact on a much smaller scale – specifically on the scale of individual low-voltage feeders. Rather than focus on the economic impact of EVs with a fixed set of parameters, the study will investigate the economic impact of various parameters on the reinforcement costs introduced by home charging of EVs. The investigations are focused on charging at private households as it is deemed important due to the number of charging facilities and a significant increase in the power consumption at households. The objective of this report is to describe the impact of various parameters on the reinforcement costs, as well as the data required to get the full potential of the identified benefits. As stated above, this study is focusing on home charging of EVs. Deployment of public and semi-public charging infrastructure might have a positive effect on the grid impact; however this is not included in this study.

2.2 Outline of This Report

Chapter 3 gives a short overview of the impact EVs have on the low-voltage grid, and the special challenges they pose.

Chapter 4 explains the method used for the study. It explains the parameters that have been used for the study. It discusses the reasoning behind the parameter choices and the limitations imposed by the used method and parameters.

Chapter 5 gives an overview of the results and presents an analysis detailing the findings of the study.

Chapter 6 puts the results of chapter 5 into perspective and discusses some of the broader implications. It also looks ahead at the future work that is required to further uncover the impact of EVs on the electrical grid and to consider EVs during grid planning.

Chapter 7 contains a conclusion which summarizes the findings of the study.

2.2.1 Terms and Abbreviations

Abbreviation	Representation	Explanation
CMS	Charge Management Strategy	The strategy or philosophy of how to charge one or more EVs in order to reach a goal.
DSO	Distribution System Operator, grid owners	The company which owns the lower voltage level grids. The company can be a privately owned enterprise, state owned or have mixed ownership.
EN	European Norm	EN in front of the number of a standard indicates that the standard is adopted by the European Committee for Electrotechnical Standardization (CENELEC).
EV	Electric Vehicle	Electric car which recharges its battery from the grid. Substitute for an ordinary commute or family car, not a truck or a train.

3 Review on EVs Impact on the Low-voltage Grid

EVs, like most other load, are connected to the low-voltage grid. However, unlike other loads EVs travel about and are therefore not always connected to the same place in the grid. Additionally, their charging depends on their usage pattern, and thus the time and duration when they draw power from the electrical grid can vary significantly. These conditions present some special challenges to the grid, especially when EVs are charged at home, as EVs are a large load compared to normal household load.

3.1 Concerns Regarding Charging of EVs

As EVs are large loads compared to normal household loads, their charging process can severely increase the load in the low-voltage grid. One of the concerns with regards to EV charging is the time of the day at which EVs are charged. The normal usage of vehicles shows that EVs will mainly be on the road during the day and connected to the grid during the evening and night. It is assumed that when users get home in the afternoon/evening, they connect their EVs to the grid and continue their day as they normally would. This means that EV charging coincides with the existing peak load of households, as residential peak load most often occurs in the afternoon/evening,. The end result is a significantly larger peak load, while the load in the remaining part of the day is unaffected. The significantly increased peak load will overload grids and require expensive grid reinforcement, in order to provide the necessary power during those few hours of the day where residential peak load and EV charging coincide.

3.2 Description of EV Charging from a Grid Perspective

EV charging and its impact on the grid depend on many factors, a description of which can be found in D4.3-B1: "*Grid Impact studies of electric vehicles_Parameters for Assessment of EVs Impact on LV Grid*". Some of the important factors from a grid perspective include charging power, charging time, which gives the energy consumption, and charging profile. The charging power determines the maximum load presented to the grid. The charging time and charging profile, determine in what time frame the grid is additionally loaded.

Without considering future features of the converter, an EV affects the grid similar to any other load. The introduction of an EV therefore requires the grid to provide more power and more energy. Providing more power gives higher loading of the grid and results in larger voltage drop.

Similar to any other load, placing an EV at the end of a long feeder will result in substantial voltage drop. On the other hand, placing that same EV at the beginning of the feeder will result in a minor voltage drop. In that regard an EV is just like any other load. There are some issues to take into consideration though, especially in regard to home charging of EVs.

Compared to the usual load of a household, an EV is a large load. The driving and usage pattern of an EV results in charging occurring at the same time as the evening load peak – a load peak that often defines the peak load of a household in both size and time. This is unfortunate, as the load from the EV is added at a time when the grid is already highly loaded.

The driving pattern of an EV, however, suggests that moving the charging process, and thus the EV load, to a different time of the day – away from the evening load peak – could be done without affecting the driving pattern. By moving the charging of the EV to a different time of the day, the power and energy required can be supplied when the grid is in a low load situation, and thus not stressed.

The ability to make the EV charging process flexible is an important aspect of EV charging. The flexibility is achieved through control of the charging process and can affect the impact that EVs have on the grid. However, this flexibility is limited by the EVs only being connected to the grid during certain times of the day. To evaluate the impact on the grid, the usage pattern of EVs - a usage pattern that closely resembles that of ICE cars - should also be evaluated.

In D4.2: *"Recommendations on grid-supporting opportunities of EVs"*[3] several ways of controlling the charging process of EVs are described. The charge management strategies that will be used in this study consist of two strategies from the conservative world category and one from the pragmatic world category. The selected charge management strategies are uncontrolled charging, time of use tariffs charging and soft charging. These strategies correspond to the user dependent, timer based and load dependent charge management strategies presented in section 4.4.3.

3.3 Parameters for Evaluation

In D4.3-B1: " *Grid Impact studies of electric vehicles_Parameters for Assessment of EVs Impact on LV Grid"* the different parameters that need to be considered when evaluating the impact of EVs on the low-voltage grid are covered. From the parameters identified in the report, the subset that will be evaluated in this study is:

- Charging Power
- Charging Profile
- EV location
- EV penetration

Charging Power

- The maximum power that the charger can draw from the grid.

The charging power is directly related to the charging time. The two are an important part of determining the charging profile. Two different charging powers are evaluated in this study – 3.7 kW and 22 kW.

Charging Profile

- A charging profile for a number of EVs: typically a curve depicting demand per hour or 15 minutes during a day.

The number of EVs which can be accommodated by the electrical grid depends on the charging profile. Three different charging profiles are evaluated in this study, representing three different charge management strategies.

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[3] Available on Green Emotion website under following link: http://www.greenemotion-project.eu/dissemination/deliverables-infrastructure-solutions.php

EV Location

- The location at which an EV is connected to the electrical grid.

The location of an EV has an impact on how the EV affects the grid. The location mainly affects the voltage in the grid.

EV Penetration

- The number of EVs in a network in relation to of the number of households.

The EV penetration specifies how many EVs are in the network at any time. As grid planning is done in relation to future load, forecasts of EV penetration are crucial to determine when grid reinforcement is required. Three different penetration forecasts are evaluated, which represent a lacking, an expected and a higher than expected deployment of EVs.

4 Methodology

4.1 Description of method

Before describing the method, it is important to align it with the goal of the study. As the goal of the study is to evaluate the influence of different parameters and the economic impact on reinforcement costs, it will be necessary to stress the networks to the point where reinforcement is necessary.

The study is performed by use of the ITRES tool[4]. ITRES is a tool developed within the Green eMotion project for assessing the reinforcement needs over a given time frame, specified in years, when the load in the network is known in each year.

An overview of the method is given in Figure 4.1.1.

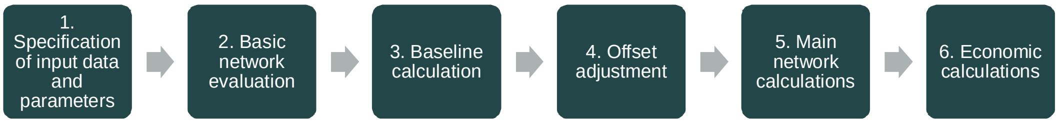

Figure 4.1.1: Overview of method used for study.

In step 1, the necessary input data and parameters are specified. This is a quite extensive task, as it requires data about the network, the existing load and the EV load in each year.

Step 2 consists of basic network calculations. This is a set of calculations performed to evaluate how many EVs the selected networks can manage before voltage or thermal issues arise. The scenarios used for these calculations can be seen in Table 8.4.1 in Appendix (Scenarios 0a to 0c). The number of EVs in the

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[4] The tool is available on the Green Emotion website under following link: http://www.greenemotion-project.eu/dissemination/deliverables-infrastructure-solutions.php

first year of evaluation is 0 and is then linearly increased until each customer has an EV (see Figure 4.4.7 in section 4.4.5).

The third and fourth steps are tied together. In step 3 a baseline calculation (Scenario 1a, see Table 8.4.1 in Appendix for details) is run to evaluate the reinforcement of the network. In step 4 the reinforcement is evaluated and the load offset adjusted. Steps 3 and 4 are repeated until the following condition is satisfied:

- The first reinforcement must occur in year 10 or earlier. The target year is year 10.

Load offset and target year are explained in section 4.4.1.

Step 5 consists of a set of calculations (Scenario 1b to 5c) that vary the parameters (see section 3.3) under study. The offset is kept constant for all calculations of a network.

The final step is the economic calculation. The output of the calculations in step 5 is used as the input for these calculations.

4.2 Description of networks

While low-voltage networks are generally designed with a radial topology, the networks differ greatly in design and topology depending on the geographical area. These differences in design and topology are necessary to facilitate the reliable supply to different customers. For instance, a low-voltage network in a rural area is notably different than a network in an urban area. A low-voltage network supplying an industrial area is notably different than a network supplying a residential area. Furthermore, the design and topology differs from country to country.
Due to these differences it has been necessary to look at different low-voltage networks. For the purpose of this study the scope of networks was limited to residential networks supplying detached houses. There were several reasons for this choice – among them was that EVs will likely have the largest impact on LV networks supplying detached houses and that networks supplying such areas are the most diverse in topology and the challenges posed. Networks supplying apartments will be affected less and in a different way, as customers are likely to have to charge their EVs from dedicated charging facilities. Such dedicated charging

facilities and public charging facilities will most likely have their own LV feeders, so the EVs will not affect the existing LV feeders.

Rather than evaluating entire networks with many feeders, low-voltage feeders were evaluated individually. This was done because the vast majority of issues and challenges experienced in low-voltage networks relate to the individual feeders due to the radial topology.

A total of 33 networks/feeders were selected for analysis. These networks cover different countries (Denmark, Italy and Spain) and different geographical areas (rural and urban) and should thus present both voltage and thermal (overload) issues.

4.3 Description of ITRES

The tool used for the calculations is ITRES. ITRES is a tool specifically developed to evaluate the impact of EVs. ITRES performs balanced 3-phase load flow calculations on the network under study. All loads are therefore considered to be 3-phase balanced loads. This of course gives some limitations that must be considered during analysis. As a lot of loads, including EVs, are single phase loads, the 3 phases will often be unbalanced. The influence of voltage and current unbalance cannot be quantified by the use of ITRES and the ITRES results could differ significantly from what is seen in practice. The main difference will be that voltage issues will be more common and occur earlier in practice than what the ITRES calculations suggest.

ITRES provides several modes of use. For the purpose of this study mode B2 is used. Mode B2 requires the user to specify the following:

- The network
- The voltage limits
- The daily load profile of each load
- The growth of load in each year of the study
- The daily load profile for a given number of EVs
- The number of EVs in each year of the study
- The cost associated with each network asset

ITRES operates with daily load profiles specified in hours, i.e. 24 load values per load profile (one day). In each year of the study ITRES performs 24 load flows, one for each hour of the day, and finds the highest loading of each component/asset

and the lowest voltage of each node. If the voltage drop is too high or any asset of the network is overloaded, ITRES will reinforce it.
ITRES offers two ways of reinforcing the assets – reinforcement mode and installation mode. In this study, installation mode is used. When an asset is reinforced in installation mode, the new size of the asset is used in all following years. Assets can be reinforced multiple times and all reinforcements are based on a separate list of assets, which specifies the electrical characteristics and price of each asset.

The output of ITRES is a reinforcement schedule specifying which assets must be reinforced in which year and why, as well as the cost of the reinforcement. An example of the output can be seen in Figure 4.3.1. What is shown is the reinforcement schedule over a 25 year time frame. The 6 categories of reinforcement are as follows:

- UG-I: Reinforcement of underground cables due to violation of thermal/current limit (overload).
- UG-V: Reinforcement of underground cables due to violation of voltage limit.
- OH-I: Reinforcement of overhead lines due to violation of thermal/current limit (overload).
- OH-V: Reinforcement of overhead lines due to violation of voltage limit.
- GMT: Reinforcement of ground mounted transformer due to violation of thermal limit (overload).
- PMT: Reinforcement of pole mounted transformer due to violation of thermal limit (overload).

In the example given in Figure 4.3.1, it is seen that a voltage reinforcement of underground cables occurs in year 3 and is the first necessary reinforcement. As the number of EVs is further increased, it also becomes necessary to reinforce the transformer. Towards the end of the 25 year period, current reinforcement of underground cables becomes necessary as their thermal limits are exceeded.

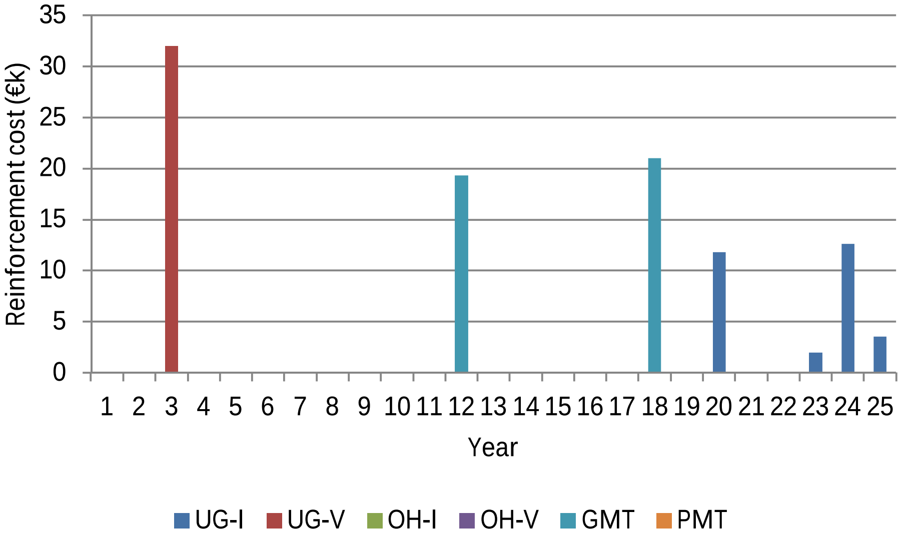

Figure 4.3.1: Example of reinforcement schedule in ITRES.

ITRES' ability to reinforce assets automatically and calculate the cost of the reinforcement is the main reason why this tool was selected for use in this study.

A more detailed description of ITRES, its features and functionality can be found in the ITRES User Manual (*ITRES User Manual, Imperial College, 2013*).

4.4 Description of used parameters

A large number of parameters must be set for each calculation. These parameters pertain to both the grid and the EVs. Some of these parameters change from calculation to calculation, while others do not. A summary of parameters and their dependencies is given in D4.3-B1: "*Grid Impact studies of electric vehicles_Parameters for Assessment of EVs Impact on LV Grid*" and it is a subset of these parameters that are investigated in this study. In order to ease the calculations, it was necessary to make simplifications to some of the parameters and their associated data.

In addition to the parameters, the value of voltage control is investigated. This is done by varying the allowed voltage drop – i.e. a larger voltage drop can be allowed along the feeder if voltage control is utilized.

4.4.1 Load

Starting with the load specification, the load is divided into two parts – existing load and EV load. Since this study focuses on detached houses, the existing load is ordinary residential load. ITRES requires a daily load profile for each existing load in the network. Since this is at best difficult to provide, it was decided to apply the same load profile to all existing loads. This load profile is based on the country of study and the number of customers.

The daily load profile of the Danish networks is based on Smart Meter measurements of individual customers. A set of load profiles covering 1 to 200 customers is generated based on these Smart Meter measurements. They present a statistical worst case situation – something akin to the 99th percentile. Details of how the load profiles are produced can be found in D4.3-B1: *"Grid Impact studies of electric vehicles_Parameters for Assessment of EVs Impact on LV Grid" (Annex 2)*. This set of load profiles gives a good representation of the daily load profile as well as the simultaneity of the loads. An overview of the load profiles is shown in Figure 4.4.1.

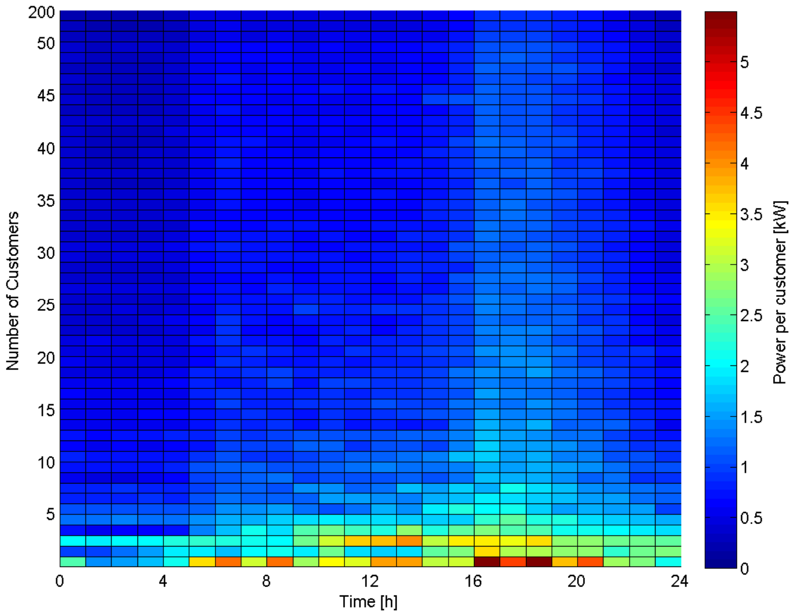

Figure 4.4.1: Load profile set for Danish networks.

The daily load profile for the Italian and Spanish networks is based on a generalized load profile. Generalized load profiles are based on measurements at higher voltage levels. Such measurements give an aggregated profile of many customers. Because such a measurement is only a single data point representing many customers, the effect of simultaneity cannot be assessed.

This effect of simultaneity results in decreasing peak load per customer as the number of customers increases. Once the number of customers is sufficiently large, the load profile coincides with the generalized load profile for residential loads. The effect of simultaneity is important and it was therefore deemed necessary to have it represented in the Italian and Spanish networks. From the Danish load data a factor is generated that expresses the effect of simultaneity. This factor is shown in Figure 4.4.2.

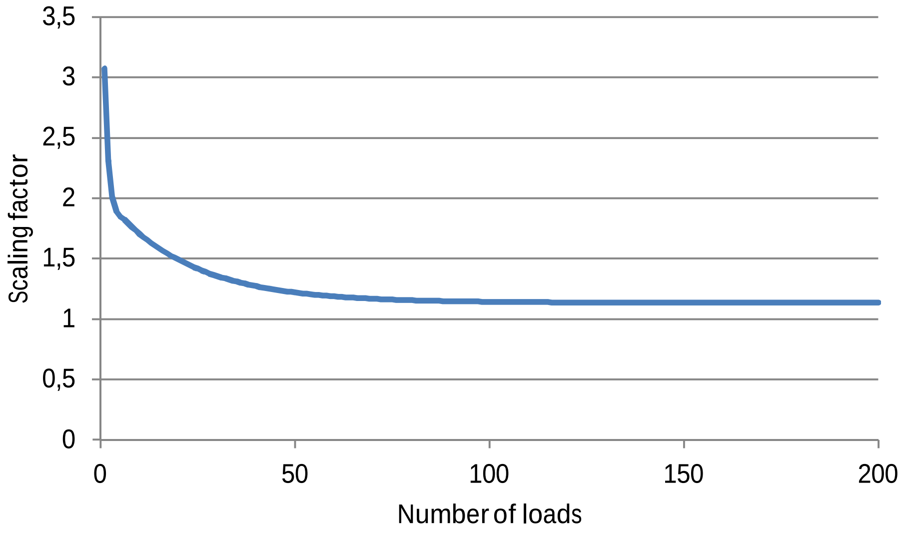

Figure 4.4.2: Scaling factor for generalized load profiles used to account for load uncertainty when dealing with few customers.

This factor is used to generate a set of daily load profiles for 1 to 200 customers that account for simultaneity for Italian and Spanish networks, based on the generalized load profile for residential loads in these countries.

This gives a complete set of load profiles covering 1 to 200 customers for each of the countries in the study. The three sets of load profiles can be found in Appendix Figure 8.1.1 - Figure 8.1.3.

In the calculations a load offset is applied. It is used to increase the load in the network until reinforcement occurs at a specific time (year 10). The load offset is a constant power added to the daily load profile of all existing loads. By increasing the load offset, the entire reinforcement schedule is moved ahead without affecting the daily load variation or the EV penetration.

An example of this is shown in Figure 4.4.3, which shows a daily load profile being offset, and the effect that it has on the reinforcement schedule. The entire schedule is moved ahead, which reveals additional reinforcement that was outside of the 25 year schedule with no offset applied. The reinforcements still occur at the same pace however, as the daily variations are unchanged.

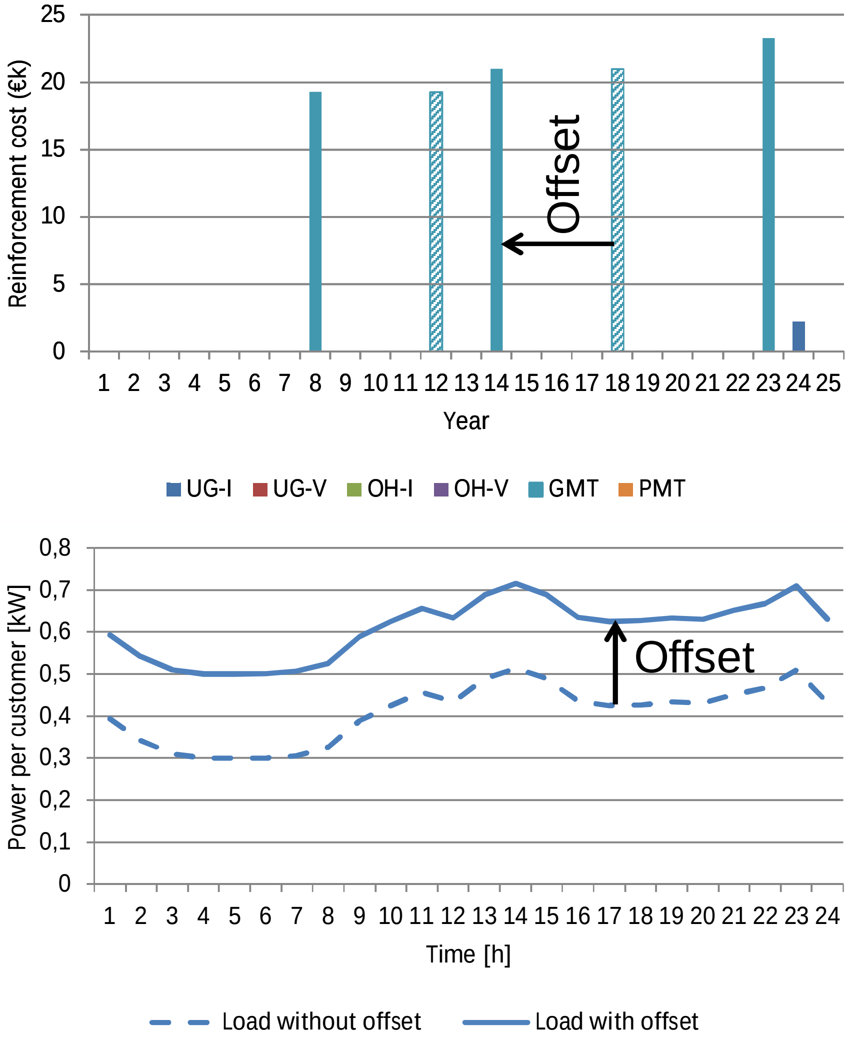

Figure 4.4.3: Example of load offset and its effect on the reinforcement schedule.

By using the offset it is possible to push the networks to the breaking point to find when issues arise and in which order the issues arise. By forcing the reinforcement schedule to begin in a predetermined year (year 10), it is possible to evaluate the influence of different parameters on the schedule. Furthermore, it is possible to align the reinforcement schedules of different networks. By aligning the reinforcement schedules of different networks, it is ensured that the EV penetration in the networks is comparable when considering the penetration as a percentage of customers, making it possible to compare the results of different networks more systematically.

Year 10 was used as the target year to assure that there would be some EVs in the networks in the target year and that it was the EVs triggering the first reinforcement, rather than the offset triggering it in year 1. While a later target year than year 10 would have resulted in more EVs at the time of the first reinforcement, it was expected that many of the scenarios would postpone reinforcements compared to the baseline. Therefore it was decided to reserve more years of the schedule for seeing postponement of reinforcements than moving ahead of reinforcements.

Load growth is not used in any of the calculations. The reason for this decision is that load growth is applied as a factor to the daily load profile – this changes the daily variation and amplifies the load peaks. Normally, such change to the load curve would be acceptable, but in this study it presents several issues.
As the load dependent charging profile is created based on the variation of the existing load, a change of the load variation would reduce the effectiveness of the load dependent profile, and it would no longer be optimal in regard to the existing load.
The use of an offset also complicates the use of load growth, as the offset is applied before the load growth factor. The net effect of this is that the applied load growth depends on the offset and is not the same for all networks, which could significantly skew the results. The effect can be explained by considering (4.4.1) and (4.4.2).

$$Load = (load\ growth)(load\ profile) + offset \tag{4.4.1}$$

$$Load = (load\ growth)(load\ profile + offset) \tag{4.4.2}$$

In (4.4.1) the load growth is only applied to the load profile. In (4.4.2), which is what happens with ITRES, the load growth is also applied to the offset. In the case of (4.4.2), the offset is no longer just shifting the reinforcement schedule, but is directly affecting the rate at which load increases.

Additionally, the omission of load growth reduces the complexity of the analysis, as there is one less parameter to consider.

4.4.2 Charging power

In this study two different charging powers are used, designated “Slow” and “Fast”:

- Slow charging is charging with a single phase 16 A charger (3.7 kW).
- Fast charging is charging with a three phase 32 A charger (22 kW).

Slow charging represents a typical home charger, as seen today. Fast charging is more representative of commercial and public chargers, but may also find use as home chargers in the future.

4.4.3 Charging profile

The charging profile of an EV will depend on the charge management strategy, the charging power and the size and state of the battery. Charging power affects the charge duration and thus the charging profile. In this study 3 different charge management strategies have been employed:

- User dependent (UD) charging
  The EV is connected to the charger as soon as the user arrives at home. The EV immediately starts charging at full power and continues charging at full power until the battery is full.
- Timer based (TB) charging
  The EV is prevented from charging in a specified time-interval. Otherwise the same as the user dependent charging – i.e. the EV is connected to the charger as soon as the user arrives at home and charges at full power (outside the blocked time interval) until the battery is full.
- Load dependent (LD) charging
  The EV is connected at home the entire day and varies its charging power depending on the load in the grid. This is an ideal scenario, where the EV uses a softcharger and has a whole day to charge its battery and the load profile of all existing loads is known.

The three charge management strategies have been selected to cover a range of control options designed to improve the grid friendliness of EVs. User dependent charging is representative of how an EV operates today when used in households. Timer based charging represents a very simple control strategy to move EV charging to a more grid friendly time of the day. In the case of introducing peak load tariffs, the result is likely to be a charging profile close to the timer based profile. The time of the day where EVs are not allowed to charge when using TB charging, is a 3 hour window covering the evening load peak. The 3 hour window is selected on a country basis according to the evening load peak. While the load profiles for Italy and Spain also have a significant load peak in the morning and noon respectively, there are no EVs connected to home chargers at these times of the day. The choice of a 3 hour window was a compromise between avoiding peak load hours and allowing the EVs enough time to charge, while keeping the control as simple as possible.

Load dependent charging is an ideal scenario that is meant to give an idea of what can be achieved if complex charge management strategies are utilized.

Based on the 3 charge management strategies, charging profiles are generated for slow charging and fast charging. The charging profiles are generated from information about time of departure, time of arrival and driving distance. Statistical data is used to produce probability density functions for each of these 3 parameters. Sampling of the three probability density functions is then used to produce the charging profiles for each combination of charge management strategy and charging power, producing 6 charging profiles. The charging profiles present a statistical worst case situation – something akin to the 99th percentile.

The 6 charging profiles are produced as sets of charging profiles. Each set contains multiple charging profiles that vary with the number of EVs. As the load profile, time of arrival and departure and driving distance are unique to each country, it has been necessary to produce the 6 charging profile sets for each country. The charging profile sets for each country can be found in Appendix Figure 8.2.1-Figure 8.2.6. The charging profile sets for Denmark are shown in Figure 4.4.4 and Figure 4.4.5 as an example.

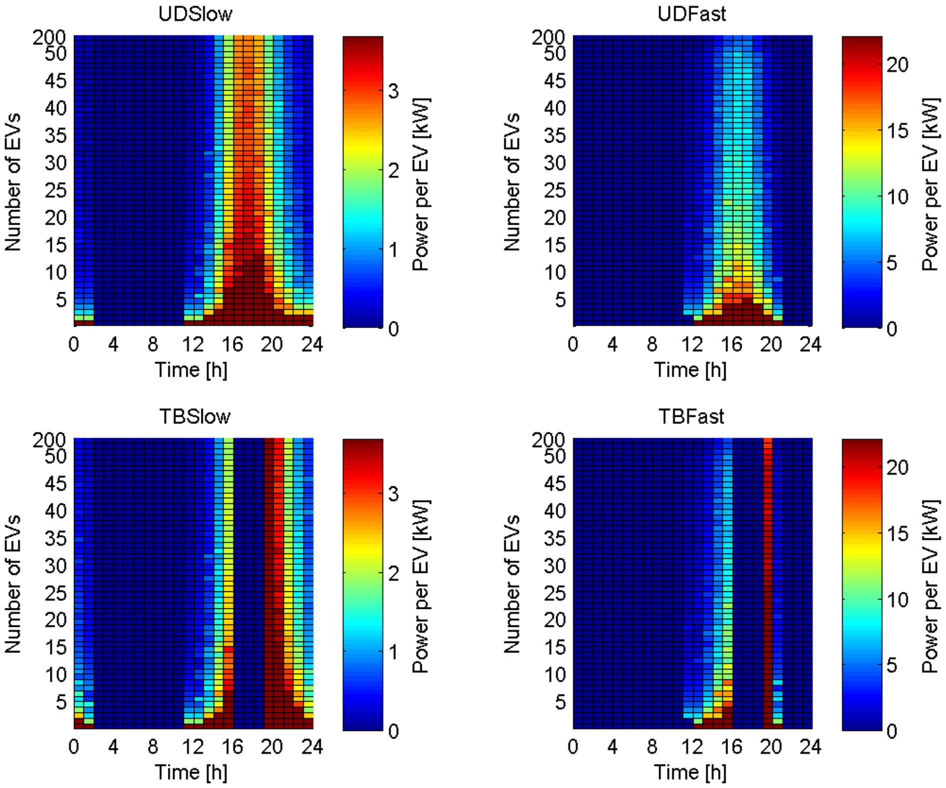

Figure 4.4.4: Charging profile sets for Danish networks for user dependent (UD) and timer based (TB) charging with slow and fast chargers.

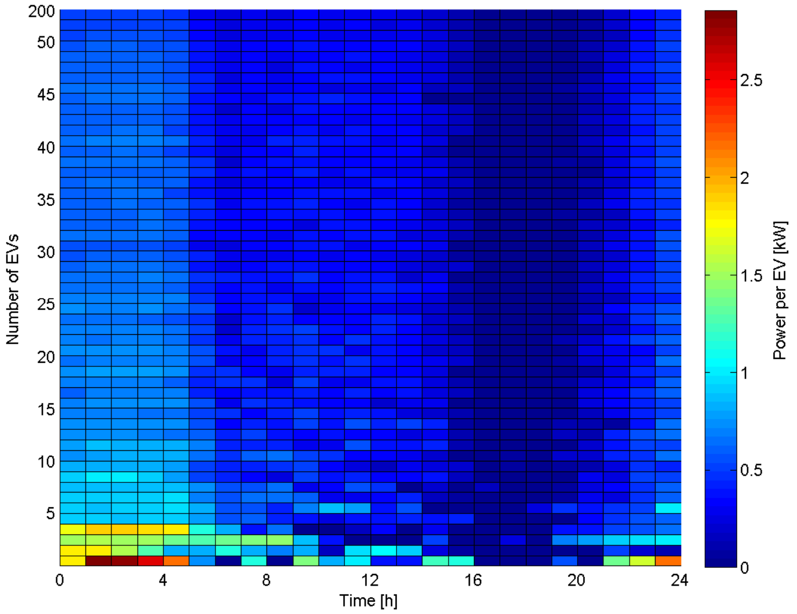

Figure 4.4.5: Charge profile set for Danish network for load dependent charging.

A more detailed description of how the charging profiles are produced can be found in D4.3-B1: *"Grid Impact studies of electric vehicles_Parameters for Assessment of EVs Impact on LV Grid" (Annex 2)*, which also explains why the method of subsampling should be used to produce the charging profiles.

4.4.4 EV location

EV location is evaluated by placing the EVs in different ways along the feeder. As the location of the EV will primarily affect the voltage, the EV placement is determined based on the voltage profile of the feeder.

- Worst case
  The EVs are placed in the nodes with the lowest voltage. If a node has several customers connected to it, then each of these customers will get an EV, before EVs are placed in any of the other nodes.
- Distributed
  The EVs are placed in the nodes with the lowest voltage. If a node has several customers connected to it, only one of them will get an EV, before moving on to the next node.
- Best case
  The EVs are placed in the nodes with the highest voltage. If a node has several customers connected to it, then each of these customers will get an EV, before EVs are placed in any of the other nodes.

Figure 4.4.6 shows an example feeder with voltage ranking of the nodes. Black numbers denote the number of customers. Red numbers are node names and denote the voltage ranking of nodes from worst/lowest voltage (1) to best/highest voltage (4). Applying the above EV placement strategies will place EVs in the nodes in the following order:

- Worst case: 1,1,2,2,3,4,4,4
- Distributed: 1,2,3,4,1,2,4,4
- Best case: 4,4,4,3,2,2,1,1

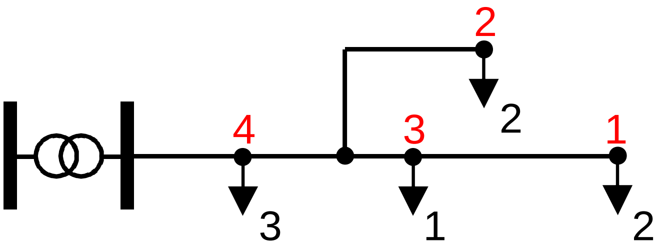

Figure 4.4.6: Example feeder/network with voltage rating of nodes.

Distributed is used as the default EV placement strategy. It gives an EV location that is neither overly pessimistic (worst case) nor optimistic (best case), but still errs on the side of caution (is closer to worst case than best case).

4.4.5 EV penetration

EV penetration is evaluated by comparing three different penetration profiles. These profiles are generated from forecasts of the number of EVs (*Energinet dk's analyseforudsætninger 2012-2035, July 2012* and *Electrification Roadmap, ERTRAC, June 2012*). The startup-phase where the number of EVs is slowly increasing is ignored and only the rate of increase during the main penetration phase is used. This is done because the very slow rate of increase in the startup-phase would skew the comparison of results for the different penetration profiles. Both forecasts estimate the accumulated number of EVs some years into the future. This data is not directly usable, as the EVs need to be distributed among the population – in this case, specifically among households. Data for the number of households in the EU was obtained from *UNECE Statistical Database (Private households by Household Type)*. Knowing the number of EVs in each year and the number of households, the EV penetration in percent in each year is calculated using (4.4.3).

$$EV\ penetration\ (year) = EVs\ per\ household\ (year) = \frac{EVs\ (year)}{households} \tag{4.4.3}$$

The three different penetration profiles are shown in Figure 4.4.7. The high profile corresponds to the high forecast for Denmark. The medium profile corresponds to the medium penetration forecast for Denmark and the high penetration forecast for EU. Both are representative of the expected evolution of EVs, based on an assumption of steady technological progress. The low profile corresponds to the low penetration forecast for the EU.

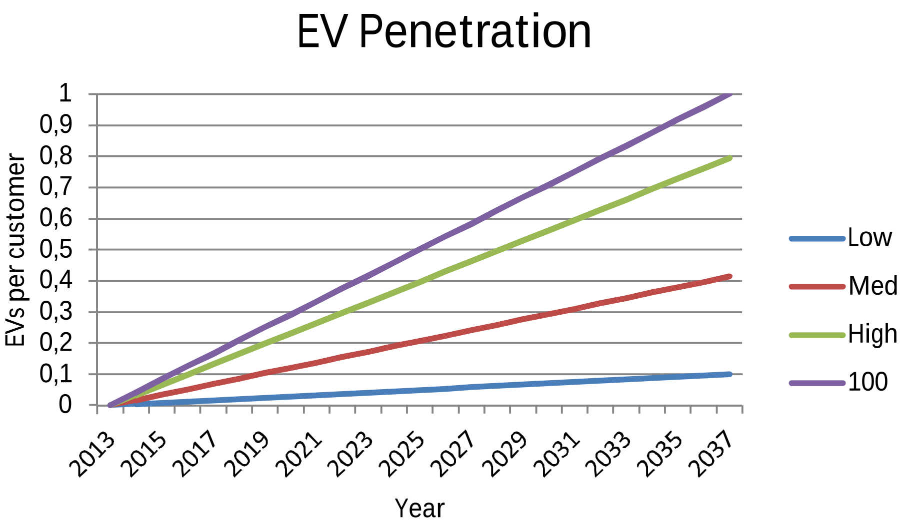

Figure 4.4.7: EV penetration profiles for main network calculations (Low, Med, High) and basic network evaluation (100).

4.4.6 Asset costs

In reinforcement mode ITRES separates the total cost into a supply cost (cost of the asset) and an installation cost (cost of installing the asset). Each asset class (underground cables, overhead lines and transformers) is divided into asset types (size of the asset), so the reinforcement cost depends on the size of the new asset – e.g. it is more expensive to reinforce with a 1000 kVA transformer than a 630 kVA transformer.

The supply cost of each asset type is based on actual costs – i.e. the costs are representative of the real price range of assets at the time of writing.

Installation costs are based on the total reinforcement costs stated by project partners and *G4V-Grid for Vehicles - D5.3: Report with the recommendations for the grid planning and operation*. The installation cost of each asset class is then adjusted, so the total cost of each asset class is roughly equal to the total reinforcement costs stated by project partners and *G4V-Grid for Vehicles - D5.3: Report with the recommendations for the grid planning and operation*.

The total cost used by ITRES should thus be representative of the real costs of reinforcement at the time of writing. The asset costs are shown in Table 4.4.1.

Asset type	Total cost (€k/km)
UG 0.4kV 50Al	69.5
UG 0.4kV 95Al	71.9
UG 0.4kV 150Al	75.0
UG 0.4kV 240Al	79.9
UG 0.4kV 300Al	83.2
UG 0.4kV Inf	88.7
UG 0.4kV Failsafe	95.0
OH 0.4kV 50Al	32.8
OH 0.4kV 95Al	35.2
OH 0.4kV 185Al	40.2
OH 0.4kV 300Al	46.5
OH 0.4kV Inf	52.0
OH 0.4kV Failsafe	65.0

Asset Type	Total cost (€k)
GMT 0.4kV 100kVA	14.0
GMT 0.4kV 200kVA	15.4
GMT 0.4kV 400kVA	18.0
GMT 0.4kV 500kVA	19.3
GMT 0.4kV 630kVA	21.0
GMT 0.4kV 800kVA	23.3
GMT 0.4kV 1000kVA	25.9
GMT 0.4kV Inf	33.8
PMT 0.4kV 50kVA	3.4
PMT 0.4kV 100kVA	3.4
PMT 0.4kV Inf	3.4

Table 4.4.1: Asset Costs for ITRES calculations.

While most of Table 4.4.1 is straightforward, there are a few things to note. Firstly, overhead lines (OH) and pole mounted transformers (PMT) are unchanged from the Asset Cost template that was supplied with ITRES. The reason for this is that it was not expected to see any PMTs in the networks, and very few, if any, overhead lines. However, prices for overhead lines were adjusted so the cost increase from size to size was similar to that of underground cables (UG).

For each asset class there is an “Inf” size. This is an “infinitely” large asset in each class. These “infinitely” large assets have electrical characteristics corresponding to 2 parallel assets of the size before “Inf”. This means that there is still a voltage drop over these components. In some extreme cases, this voltage drop would require voltage reinforcement of “Inf” assets, which would cause the ITRES calculation to fail.
Due to this, it was necessary to add a “Failsafe” size for underground cables (UG) and overhead lines (OH). These “Failsafe” asset types have zero impedance and thus no voltage drop.

4.5 Description of economic calculations

The economic calculations are an important part of this study. While the network calculations should give a good view of how the different parameters affect the reinforcement schedule, it is the economic calculations that will reveal the value of delaying and avoiding reinforcements. From an economic point of view, this value is what will drive the market and what is available for investments in an attempt to make EVs part of a more intelligent energy system. The economic calculations will attempt to quantify that value.

In ITRES each reinforcement is associated with a cost. That cost is the investment that needs to be made in each year of the reinforcement schedule. The cost is defined according to the asset it concerns and categorized according to the kind of issue it resolves. As the reinforcement cost is categorized by the issue it resolves, it should be possible to determine which issues are more costly and thus more valuable to delay or avoid.

The vast majority of the economic comparisons are made between three scenarios. The economic calculations are therefore constructed to calculate the cost of three scenarios and present and compare the results of these three scenarios.

Each scenario (A, B, and C) provides an investment horizon for six grid reinforcement categories over a 25 year time span. These investment horizons are the reinforcement schedules produced by ITRES (see section 4.3) for the cases that will be compared. A decision maker needs to understand the value of each scenario and compare them individually in order assess the best option at hand. A list of all scenarios can be found in Appendix Table 8.4.1.

The value from deferred investments is generated from the time value of money concept. An investor is better off investing 1 million Euros next year than today, as it gives the opportunity to invest the 1 million Euros now and earn an interest. A way of expressing this in the scenario comparisons is to use the method of net present value (NPV).

To calculate the value of each investment scenario, all the investments are turned into annual amortization representing the annual depreciation and interest payment of each year.[5] In the six grid asset categories multiple investments within the same category can occur at different times, and the amortizations start from the first year and runs throughout the economic lifetime of the asset. The value generated simply arises from two drivers; the value of the investments, and the difference in timing of the annual amortization.

The decision for which path to choose is taken in year 0. Therefore all investments must be discounted back to the value they represent in year 0 in order to allow decision makers to make the right choice. After lining up the annual amortizations, starting in different years they must be discounted back to year 0, to factor in value of the lost opportunity which could have been achieved if an investor had chosen to keep the money in the bank and earn risk-free interests. The present value of each investment can now be summed and the scenarios can be compared accordingly (i.e. based on the NPV).

In the comparison, the potential revenues are neglected and the risk associated with each scenario is assumed to be the same across investments and scenarios. Therefore, the right financial metric is the present value which represents the value of investments in each scenario in year 0, as explained above. Assuming that potential revenues and the associated risk is the same across scenarios, a decision

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[5] In the calculations an economic lifetime of 35 years, a WACC of 7% and socio-economic discount rate of 5% are assumed.

maker is best off choosing the scenario which represents the lowest present value of investments.

5 Results and Analysis

As the complete results of the study consist of a large amount of data, the full results will not be presented in this report. Instead a summary of the main tendencies seen in the results will be given, with illustrative examples and a limited range of the complete results.

5.1 General Analysis

Before going into analysis of the different parameters, a simple evaluation of the networks is done with a fixed set of parameters (Calculation 0a to 0c). The networks are evaluated with distributed EV location and slow chargers. Each of the three charging profiles is evaluated with an EV penetration that increases linearly from 0 to 100% throughout the 25 year timeframe of the ITRES calculations (see Figure 4.4.7).

The results are summarized in Table 5.1.1. As seen in Table 5.1.1, most of the networks require reinforcement to accommodate 100% EVs. However, a large part of the networks can accommodate a significant amount of EVs (more than 30%), without any reinforcement. It is important to note that the charge management strategy is a crucial factor in determining how large an EV penetration the networks can accommodate before reinforcement is necessary. With load dependent charging, all the networks can accommodate 100% EVs, except for Network 30, which requires reinforcement in the first year in order to accommodate the existing load of the network.
Timer based charging has a mixed influence, increasing the EV penetration before first reinforcement in some networks and reducing it in others. The reason for this behavior is a kickback effect that occurs in the timer based charging profile. A more detailed description of the kickback effect can be found in section (charge profile).

	User Dependent Charging First Reinforcement		Timer Based Charging First Reinforcement		Load Dependent Charging First Reinforcement	
Network	Year	EVs (%)	Year	EVs (%)	Year	EVs (%)
1		100%	24	95%		100%
2	22	89%	21	82%		100%
3	7	26%	7	26%		100%
4	3	9%	5	17%		100%
5	9	32%	9	32%		100%
6	4	13%	4	13%		100%
7	13	52%	13	52%		100%
8	4	14%	5	18%		100%
9	12	46%	13	54%		100%
10	10	38%	10	38%		100%
11	19	75%	20	81%		100%
12	19 19	77%	21 21 21	82%		100%
13	17	70%	17	70%		100%
14		100%		100%		100%
15	21	86%	21	86%		100%
16		100%		100%		100%
17		100%	20	79%		100%
18	22	88%	18	70%		100%
19		100%		100%		100%
20	7	25%	8	28%		100%
21	22	88%	17	67%		100%
22	12	46%	11	41%		100%
23	6	20%	6	20%		100%
24		100%		100%		100%
25	17	66%	13	51%		100%
26	14	54%	12	46%		100%
27		100%		100%		100%
28	11	42%	9	33%		100%
29	10	38%	8	29%		100%
30	1	0%	1	0%	1	0%
31	24	95%	17	68%		100%
32	2	5%	3	9%		100%
33		100%		100%		100%

Table 5.1.1: Summary of general analysis. Highlights indicate the nature of the reinforcement – voltage (red), current (blue) or transformer (cyan).

5.2 Baseline Analysis

The baseline calculation (calculation 1a) is made with medium EV penetration, distributed EV location, slow chargers and an allowed voltage drop of 5%. EN50160 specifies that voltage must remain within ±10% of nominal value. Since this voltage range covers voltage variation from all voltage levels, only a fraction of this voltage range can be allocated to voltage variation in the LV grid. An allowed voltage drop of 5% is used because it is assumed that the rest of the EN50160 voltage range must be reserved for voltage variations in the medium voltage grid and the distribution transformer.

Table 5.2.1 shows an overview of the networks, specifying number of customers, length and offset. It also details the kind of reinforcements that occur in each network and in what year they occur.

Network	Customers (#)	Length (m)	Offset (kW)	Total Offset Power (kW)	Reinforcement			
					Voltage	Current	Transformer	First
1	38	292	2.7	102.6		10,25	18	C
2	28	507	2.2	61.6	9		23	V
3	31	406	0.2	6.2	19		10,17	T
4	69	518	0	0	6			V
5	28	241	0.6	16.8			9,19	T
6	70	629	0	0	7		24	V
7	21	250	1.25	26.25		8,14	19	C
8	28	634	0	0	9			V
9	13	286	1.05	13.65			8,22	T
10	42	453	0.6	25.2	10		22	V
11	16	205	2.3	36.8			7	T
12	22	234	2	44	8		13	V
13	10	108	2	20			10	T
14	26	458	3.7	96.2			9	T
15	14	227	2.5	35			8,24	T
16	9	519	6.4	57.6	5			V
17	43	116	2.3	98.9		10,25		C
18	50	74	1.8	90		10	21	C
19	14	317	4.4	61.6			8	T
20	53	100	0.3	15.9			10,15	T
21	51	181	1.7	86.7		10,11	15	C
22	80	110	0.8	64		10,11,23		C
23	59	166	0.2	11.8		24	8,14,23	T
24	11	13	4.2	46.2			9	T
25	47	191	0.85	39.95			10	T
26	57	80	0.7	39.9		22	10	T
27	9	91	3.8	34.2	-	-	5	T
28	103	173	0.35	36.05	-	9,21	-	C
29	100	167	0.3	30	-	16,24	9,24	T
30	252	606	0	0	1,23	Many	13,20	C
31	19	124	1.6	30.4	-	-	9	T
32	66	871	0	0	4,13	-	-	V
33	1	0	20	20	-	-	1	T

Table 5.2.1: Summary of networks and baseline results showing number of customers, length, offset, reinforcements and first reinforcement. For reinforcement, colors indicate reinforcement type and numbers indicate years in which reinforcement occurs.

The networks can be divided into three groups:

- Networks requiring voltage reinforcement
- Networks requiring current reinforcement
- Networks requiring transformer reinforcement

The voltage reinforced networks are characterized by a high length (more than 400m to farthest node/load). There is one exception, and that is Network 12, which has a length of 234m and 22 customers. This network is rather weak however, with the first 80m of it being 35mm^2 aluminum cable, and 18 of the 22 customers placed towards the far end of the feeder. Thus those 80m of 35mm^2 aluminum cable are supplying nearly all the customers, resulting in a high voltage drop across this part of the feeder.

The current and transformer reinforced networks are generally short (less than 300m to the farthest node/load). A large part of them are very short (less than 150m). There is one exception, and that is Network 14 with a length of 458m and 26 customers. This network would be expected to be voltage reinforced, but the feeder is constructed from 240mm^2 and 150mm^2 aluminum cables and a fairly small transformer. Due to this, the transformer needs to be reinforced before the network runs into any voltage issues. Closer inspection shows that the network is close to violating the voltage drop limit and had it been supplied by a larger transformer would likely run into voltage issues first.

For the current reinforced networks it generally applies that they have many customers (more than 50). The high amount of customers on the feeders means that a larger percentage of the transformer rating is reserved for those feeders, and thus the cable ratings are exceeded first. However, outside of a few exceptions, all the current reinforced networks are also transformer reinforced. For the few exceptions, the reserved transformer rating is high (more than 200 kVA).

The transformer reinforced networks generally have few customers (often less than 20). The reason for this is that when a feeder has few customers, less of the transformer rating is reserved for the feeder. More notably, the reserved transformer rating is mostly between 50 and 100 kVA for the feeders that are transformer reinforced first. As most feeders start with 95mm^2 or 150mm^2 aluminum cables, which are rated at roughly 120 and 150 kVA, the transformer will be reinforced first if the reserved rating is less than those values.

There are a few networks that need special mention, as they present some special cases.

- Network 30 is voltage and current reinforced in year one. At this point in time, there are no EVs in the network, so the existing load is more than the network can handle.
- Network 33 is transformer reinforced in year one. This network consists of a single customer connected directly to the transformer, so only transformer reinforcement can be expected.
- Networks 28 and 29 both have a cable reinforcement to "Inf" (see section 4.4.6), indicating that in these two networks low-voltage cable reinforcement may not be sufficient and that more extensive reinforcement in the form of MV reinforcement may be necessary.

5.3 Voltage control

Voltage control can be used to avoid voltage reinforcements in networks, but has no real effect on other types of reinforcement. Thus this section is only of interest in regard to the voltage reinforced networks.

Voltage control in low-voltage networks can be performed in different ways. For this study, the way of performing voltage control is not of interest. The use of voltage control allows for better utilization of the allowable voltage range specified in EN50160 – i.e. less of the voltage range in EN50160 has to be reserved for voltage variations in the medium voltage grid and distribution transformer. This better utilization is expressed in these calculations by allowing a larger voltage drop in the LV network. This is practically done by changing the voltage setpoint and minimum voltage for the calculations (see scenario 2.1 and 2.2 in Table 8.4.1). The economic comparison to the base case (scenario 1a) for all networks can be found in Appendix Table 8.3.3 and Table 8.3.4.

5.3.1 Network impact

For the voltage reinforced networks, the results show that voltage control results in big changes to the reinforcement schedule. For current and transformer reinforced networks, however, voltage control is of no importance.

It is found that voltage reinforcements are entirely avoided by allowing up to 10% voltage drop instead of the usual 5%. Increasing the allowed voltage drop to 15% has no additional benefits. As such the results show that if moderate voltage control is applied, so that a voltage drop of up to 10% can be allowed in the low-voltage network, then voltage reinforcements can be avoided.

However, the results also show that some lines will need current reinforcement instead. Transformer reinforcement on the other hand is unaffected. Some minor changes in the year of transformer reinforcement may occur due to a change in network losses. An example is shown in Figure 5.3.1.

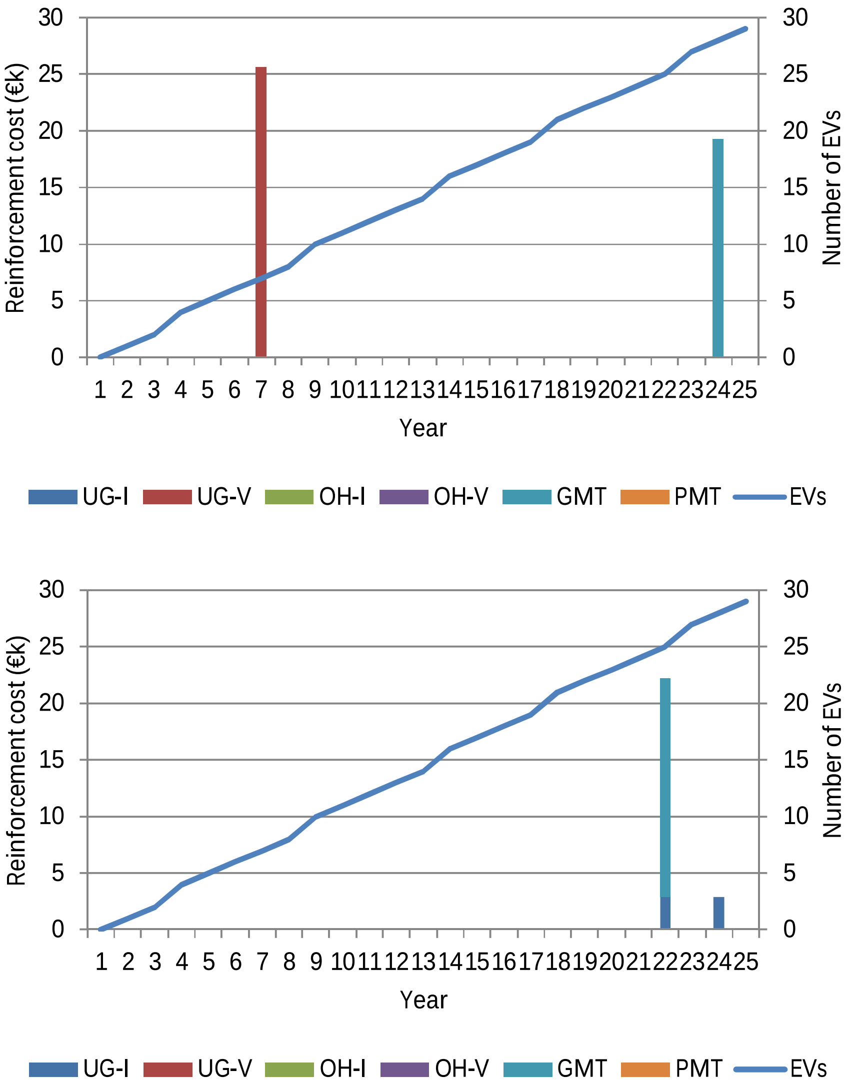

Figure 5.3.1: Baseline (top) and voltage controlled (bottom) reinforcement schedules for Network 3.

5.3.2 Economic impact

As voltage reinforcements are usually fairly extensive in nature, the economic impact of avoiding them is quite significant. While not all voltage reinforced networks have voltage reinforcement as the first reinforcement, the results of all voltage reinforced networks are very similar. On average, the reinforcement costs are 19.8 €k lower in the networks with voltage control, with sums varying from 7.6 €k to 30.8 €k. In terms of network value this corresponds to an average of 28.2% with variations from 14.4% to 40.6%.

5.3.3 Subconclusion

The results show that with a moderate amount of voltage control (i.e. a larger allowed voltage drop), voltage reinforcement can be entirely avoided in all the studied networks, leading to an average economic gain of 19.8 €k for the networks that required voltage reinforcement.
The limited amount of voltage control required to avoid voltage reinforcements and the fast following current reinforcements in some of the networks indicate that reactive power may not be a useful solution of voltage issues in some low-voltage networks – especially given their low voltage sensitivity to reactive power.

5.4 Location

Location is primarily important in regard to voltage and voltage reinforcement. While it also affects current reinforcements, it does so to a much lower degree. This section is based on scenarios 3.1 and 3.2 and the different ways of distributing the EVs are explained in section 4.4.4. For economic comparison to the base case (scenario 1a) for all the networks see Appendix Table 8.3.5 and Table 8.3.6.

5.4.1 Network impact

For voltage reinforced networks, a best case EV location will either delay voltage reinforcement significantly (more than 5 years) or avoid it entirely compared to distributed EV location. Some of the lines that were previously voltage reinforced will have to be current reinforced instead, while transformer reinforcement is unaffected. For current reinforced networks, some lines are reinforced later, or the reinforcement avoided. This is not surprising, given that fewer lines are being loaded by the EVs, as they are all placed at the beginning of the network/feeder. However the effect is fairly limited, the lines at the beginning of the network are usually the strongest, thus requiring a significant amount of EVs before they are overloaded.

Looking at worst case EV location, it is found that in most cases, there is little difference in the reinforcement schedule compared to the distributed case. This is because the networks often have few customers at the far end, and thus the EV locations in the two cases end up being very similar. In networks where there are more customers at the far end, worst case EV location results in voltage and current reinforcements having to be made earlier and sometimes also requires more lines to be voltage or current reinforced.

An example of how location impacts the reinforcement schedule of voltage reinforced networks is shown in Figure 5.4.1.

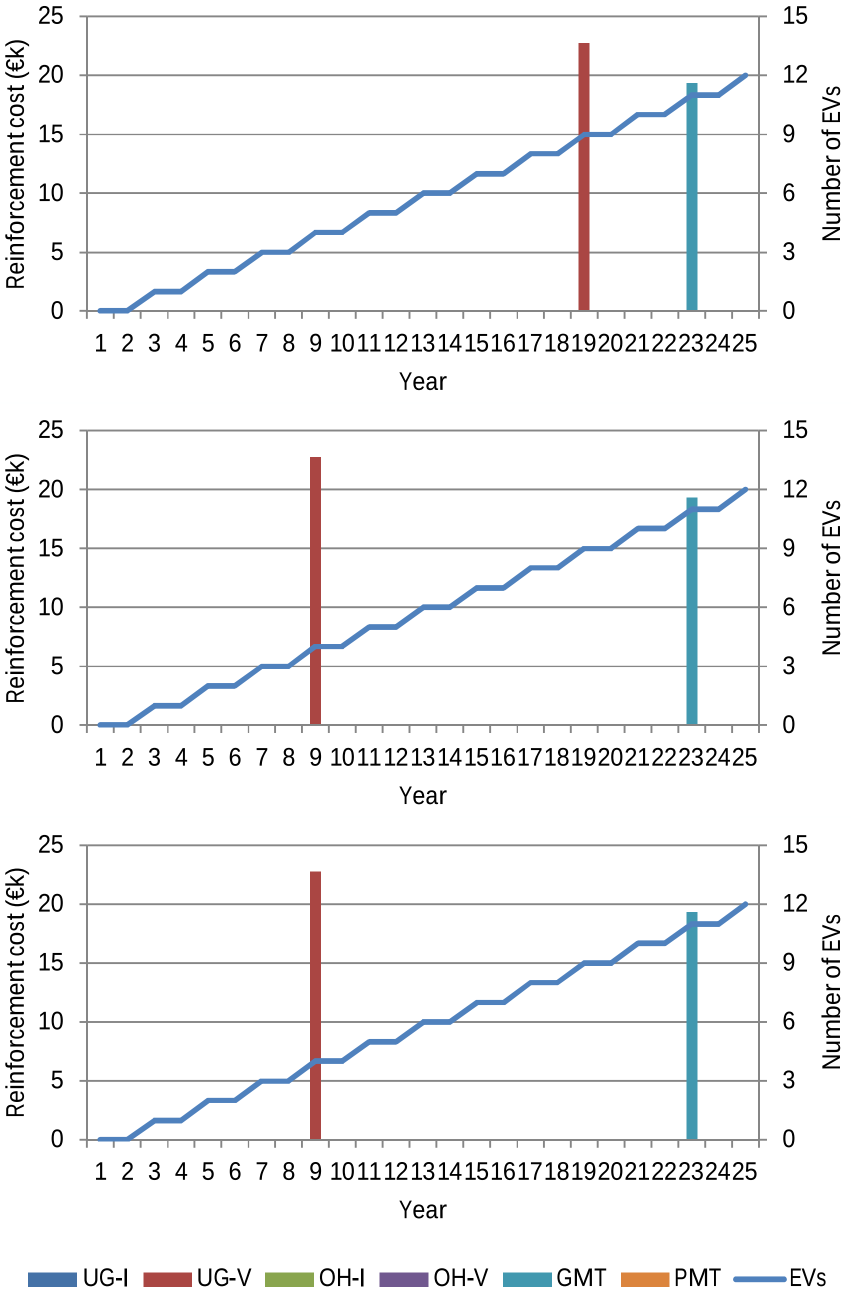

Figure 5.4.1: Reinforcement schedules for Network 2 for best case (top), distributed/baseline (middle) and worst case (bottom) EV location.

5.4.2 Economic impact

The network results showed that it was primarily the voltage reinforced networks that were affected. The economic results reflect the network results and show that location can be a quite important parameter for these networks.

Looking at best case EV location the economic results show that for voltage reinforced networks, the economic gain compared to the distributed case is 13.3 €k on average, spanning values of 7.2 €k to 22.8 €k. In terms of network value this corresponds to an average of 18.8%, with variations from 8.3% to 35%. Looking at all other networks, most see no difference. For those that do, the best case distribution gives a reinforcement cost that is on average 1.9 €k lower, corresponding to 4.9% of network value. This result, however, is heavily affected by Network 29, which sees an economic gain of 8.3 €k, corresponding to 23.1% of network value.

When comparing the distributed case to the worst case, it is found that on average the reinforcement costs for voltage reinforced networks are 5.3 €k higher with the worst case distribution of EVs. In terms of network value this corresponds to 7% of network value. While the majority of the other networks do not see an economic effect between the two distributions, some do. For those that do, the average reinforcement costs are 725 € higher (corresponding to 2.1% of network value), which is a very moderate amount.

5.4.3 subconclusion

The results show that for current and transformer reinforcements, the location is of little importance given that neither the network nor economic impact is significant in any of the networks. The location of EVs is only important in networks that experience voltage issues, where the average economic difference between worst case and best case EV location is 18.6 €k.

5.5 *Charging profile*

This section is based on many different scenarios, as the charging profiles depend on the number of EVs and the charging power. The charging profiles are explained in section 4.4.3. For economic comparisons between the charging profiles for all the networks see Appendix Table 8.3.1, Table 8.3.2 and Table 8.3.7 to Table 8.3.12.

5.5.1 Network impact

The effect of changing the charging profile is compared across several cases, namely low, medium and high penetration. Going from user dependent charging to timer based charging, it is found that for a low number of EVs the effect on the reinforcement schedule is positive. The peak load is reduced by moving the EV charging away from the existing load peak.
However, with a higher number of EVs, the effect on the reinforcement schedule is negative. The peak load increases, but the time at which the peak load occurs has changed. The peak occurs in the hour after release of the EVs. The reason for this is a kickback effect that occurs when preventing the EVs from charging in a given timeframe. With a high number of EVs the effect of simultaneity will reduce the EV peak load. However, when the EVs are prevented from charging in the existing load peak, the effect of reduced simultaneity will be removed and the EVs will no longer have their charging distributed across the evening hours. Instead they will all charge at the same time and thus produce a higher peak load. The higher the amount of EVs, the more pronounced the kickback effect. This is clear from Figure 4.4.4, where the charging profiles for user dependent and timer based charging are shown.

With low penetration the overall effect in the networks is positive. This is due to the low amount of EVs introduced in the low penetration case.

In the medium penetration case, the effect largely depends on the number of customers. In networks with few customers, the overall effect is positive and reinforcement is delayed or avoided. In networks with many customers and thus many EVs, the effect is different. The first reinforcements are delayed, as the number of EVs is low in the beginning of the reinforcement schedule. But as the number of EVs increases, during the last years, the kickback effect takes over and the later reinforcements are moved ahead and the amount of reinforcement increases. The overall effect when evaluating the final year is therefore negative. An example of the effect of kickback on the reinforcement schedule is shown in Figure 5.5.1.

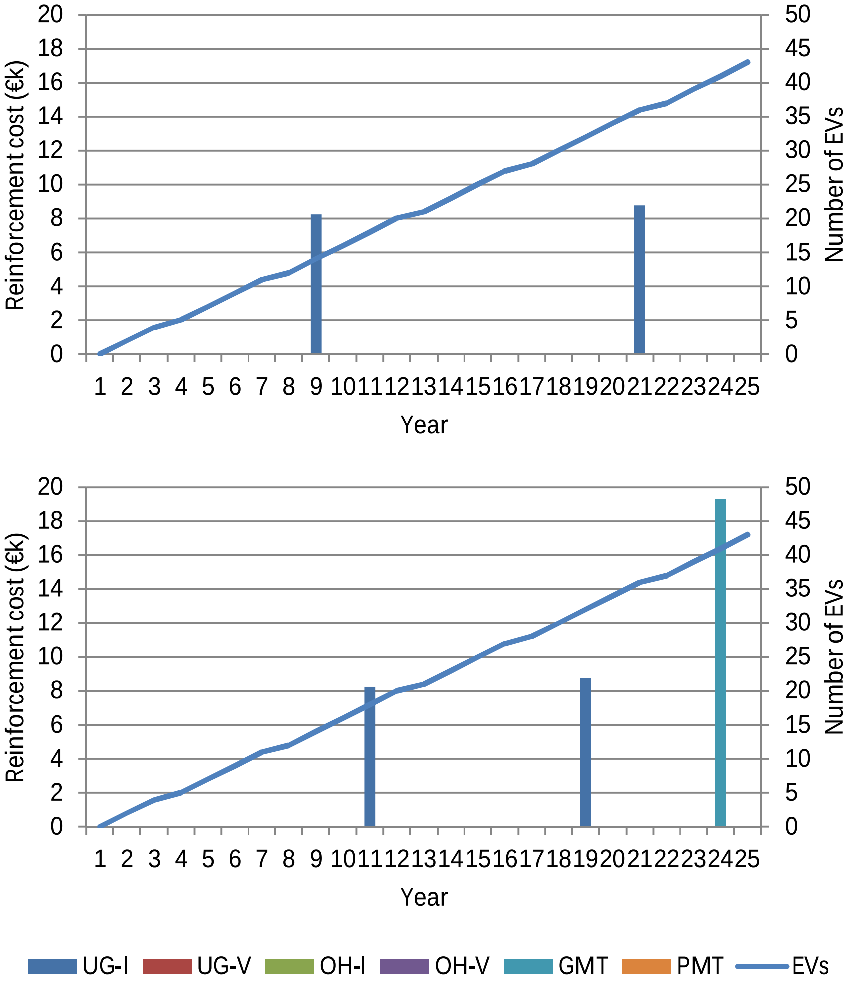

Figure 5.5.1: Reinforcement schedules for Network 28 with medium EV penetration and user dependent (top) and timer based (bottom) charging.

For the high penetration case, the effects seen in the medium penetration case continue. As the number of EVs is higher in this case, the overall effect on the networks is much more affected by the kickback effect and the effect on the reinforcement schedules is more negative overall.

In the fast charging case, the kickback effect is much more pronounced, as is clear from Figure 4.4.4. As such, the use of the timer based charging profile has a very negative effect on the reinforcement schedule.

The load dependent charging profile removes the need for all reinforcements, as it does not increase the peak load of the networks. The exception to this is found in the case of the Spanish networks. The reason that these networks still see an amount of reinforcement is that the idealized load dependent charging profile actually increases the peak load of the networks, as all the energy required by the EVs cannot be moved away from the existing load peak.

5.5.2 Economic impact

The economic effect of controlling the charging profile is very mixed, when comparing the timer based charging profile to the user dependent charging profile. The reason for this is the kickback effect seen with timer based charging.

Starting with the low penetration case, most of the networks do not require any reinforcement. However, looking at the networks that do require reinforcement there is an economic gain of 8.7 €k on average, with values spanning from 3.9 €k to 14.6 €k. In terms of network value this corresponds to an average of 18.1%, with variations from 2.9% to 47%.

Looking at medium penetration the economic results are quite different. The average economic gain is 90 € if viewed across all 33 networks. That average is a result of 3 distinctly different cases – networks where an economic loss is seen, networks where no economic impact is seen and networks that see an economic gain. The networks where an economic gain is seen as a result of moving from user dependent charging to timer based charging on average see an economic gain of 3.3 €k (corresponding to 8.5% of network value). However, the networks where there is an economic loss have an average loss of 5.7 €k (corresponding to 13.5% of network value). This shows that in the networks used in this study, there are more networks that experience a positive impact from using timer based charging, than there are networks which experience a negative impact.

The high penetration case continues the trend seen in the medium penetration case. However, the negative impact from kickback is much more apparent in the high penetration case. Looking across all networks, there is an average economic loss of 6.3 €k (corresponding to 14% of network value). This comes from many of the networks experiencing a significant kickback effect. For the networks experiencing a loss, the average economic loss is 11.4 €k (corresponding to 26.3% of network value). The networks that see an improvement see an average economic gain of 2 €k (corresponding to 6.2% of network value). A few of the networks see no economic impact.

Comparing the load dependent charging profile to the user dependent charging profile, the economic gains from using load dependent charging largely mirrors the reinforcement costs with user dependent charging. This is not surprising given the network results, which showed that using load dependent charging prevented reinforcement in nearly all networks, as it moved the EV charging entirely away from the existing load peak. This is true regardless of EV penetration.
The average economic gains across all networks for low, medium and high EV penetration are 11.4 €k, 21.5 €k and 38.5 €k, respectively. In terms of network value this corresponds to 19.2%, 50.5% and 92.8%.

5.5.3 Subconclusion

The results for timer based charging show that even simple control of EV charging can be of benefit to the grid. However, attention must be paid to kickback. As the results show, the kickback effect can be a severe issue and end up loading the networks more than when no control is applied to EV charging, thus leading to increased reinforcement costs. Kickback presents a serious issue that must be addressed by any charge management strategy that aims to move EV charging away from the existing peak load. If kickback is controlled, even simple measures like timer based charging could benefit the network and postpone reinforcements several years.

Looking at complex charge management strategies, the results for load dependent charging show that in most cases EV charging can be moved entirely away from the existing load peak. Load dependent charging avoids all reinforcement of the networks and the associated costs, and shows the value that a complex charge management strategy can provide.

5.6 EV penetration

This section is based on scenarios 4.1 and 4.2. The EV penetrations used are explained in section 4.4.5. For economic comparisons between the EV penetrations for all the networks see Appendix Table 8.3.13 to Table 8.3.18.

5.6.1 Network impact

When it comes to EV penetration, each charging profile must be viewed separately. Starting with the user dependent profile, it is clear that the EV penetration has a large impact on the reinforcement. In the low penetration case, most of the networks require no reinforcement to deal with the load. For the few networks that do require reinforcement, compared to the medium penetration case, the reinforcements are postponed significantly and occur during the last years of the reinforcement schedule.

A high EV penetration results in significantly higher amount of reinforcement. The reinforcement schedule is also pushed forward. In several of the networks lines are reinforced multiple times and end up being reinforced to “Inf”. This means that traditional line reinforcement may not be sufficient, and that a more extensive reinforcement may be required – i.e. an MV grid reinforcement. An example is shown in Figure 5.6.1.

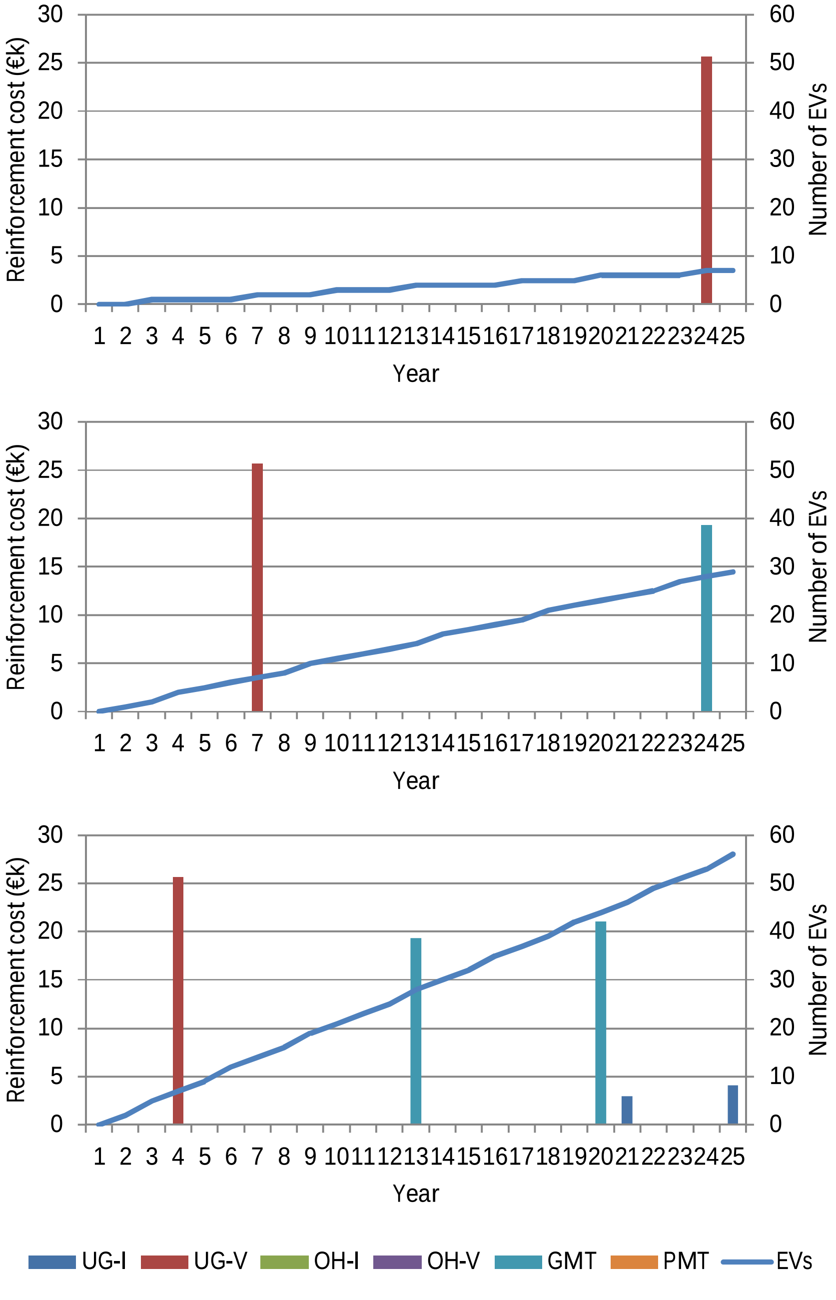

Figure 5.6.1: Reinforcement schedules for Network 6 with low (top), medium/baseline (middle) and high (bottom) EV penetration and user dependent charging.

For the timer based profile, low penetration requires no reinforcement, outside of a couple of voltage reinforced networks that still require some reinforcement. In the

two voltage reinforced networks that do require reinforcement, the reinforcement is postponed significantly.
In the high penetration case the need for reinforcement increases significantly compared to the medium penetration case. A significant part of the networks requires line reinforcement to “Inf”, and a few require transformer reinforcement to “Inf”. Traditional line and transformer reinforcement may not be sufficient for these networks and a more extensive reinforcement in the form of MV reinforcement may be necessary.

Looking at the load dependent profile, penetration has no influence on the reinforcement of most of the networks. The exception consists of a two Spanish networks that require transformer reinforcement in the late years of the high penetration case. This is because EV charging during the existing load peak cannot be entirely avoided in with the Spanish load profile, and with a high amount of EVs the increase in peak load is significant enough to require reinforcement.

5.6.2 Economic impact

Starting with user dependent charging, the average economic gain of moving from a medium EV penetration to a low EV penetration is 19.1 €k, spanning values of 0 to 51.3 €k. In terms of network value this corresponds to an average of 46.4%, with variations from 0% to 134%. Moving from medium to high EV penetration results in an average economic penalty of 17.5 €k, spanning values of 0 to 48.9 €k. In terms of network value this corresponds to an average of 43.3%, with variations from 0% to 131%.

Looking at the timer based case, the average economic gain of moving to low EV penetration is 20.6 €k, spanning values from 0 to 73.7 €k. In terms of network value this corresponds to an average of 49.1%, with variations from 0% to 134%. Moving to a high penetration incurs an average economic penalty of 23.9 €k, spanning values of 0 to 59.1 €k. In terms of network value this corresponds to an average of 57.9%, with variations from 0% to 185%.

In the case of load dependent charging, EV penetration plays no real role, as the EVs do not increase the peak load of the networks. Two networks see an impact from EV penetration. Both require transformer reinforcement in the late years of the high penetration case, resulting in an economic penalty of 7.6 €k, compared to the medium penetration case. This corresponds to 17% of network value.

5.6.3 Subconclusion

The results show that the influence of EV penetration depends highly on the charging profile of the EVs. If the charging of the EVs is distributed well across the day by the use of an efficient charge management strategy, then EV penetration becomes less important. However, if the charging of EVs is not distributed well across the day, as is the case with user dependent and timer based charging, the reinforcement requirements and costs depend highly on the EV penetration. This stresses the importance of good forecasts of EV penetration.

5.7 Charging power

This section is based on scenario 5. Charging powers are explained in section 4.4.2. For economic comparisons between charging powers for all the networks see Appendix Table 8.3.19 to Table 8.3.24.

5.7.1 Network impact

The charging power has a very large influence on the reinforcement schedule of the networks. Its influence however, depends highly on the charge management strategy. For the load dependent charging profile, there is no difference between the use of a slow and fast charger. The reason for this is that the charging power depends on the load and never exceeds the power limit of the slow charger.

For the user dependent charging profile, the increase in charging power overloads almost all the networks beyond what can be handled with conventional line and transformer reinforcement and more extensive reinforcement will likely be necessary – i.e. reinforcement of the MV grid. It is primarily the lines that need heavy reinforcement, as they end up being reinforced to “Inf” in many of the networks. The transformers end up being reinforced to “Inf” in a handful of networks and do not require reinforcement as badly as the lines. See Figure 5.7.1

for an example of the significant increase in reinforcements and reinforcement costs.

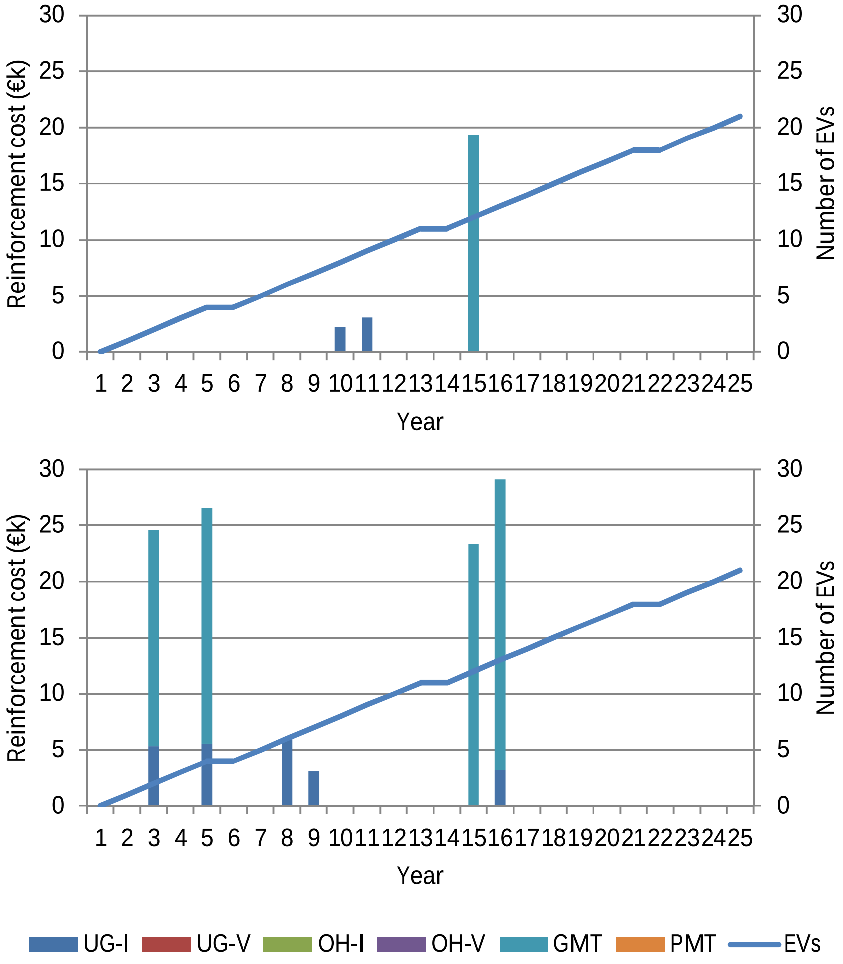

Figure 5.7.1: Reinforcement schedule for Network 21 with slow/baseline (top) and fast (bottom) chargers.

With timer based charging, the reinforcement requirements are even more severe than with user dependent charging – and to such a degree that practically all the networks have lines and transformers reinforced to “Inf”. The kickback effect with fast charging is much more severe, and puts the full load of nearly all EVs in the hour after release. With the higher power of fast chargers, the peak load is tremendous and far beyond what the networks can handle.

5.7.2 Economic impact

Looking at charging power, the network impact was quite severe, requiring large parts of the networks to be reinforced several times. The economic impact is very severe as well. With user dependent charging, the average economic penalty of fast chargers instead of slow chargers is 73.9 €k (corresponding to 181% of network value). With timer based charging, where the kickback effect plays a larger role, the average economic penalty of going from slow chargers to fast chargers is 101.1 €k (corresponding to 239% of network value). For the load dependent charging, there is no difference as the charging power remains lower than the 3.7 kW limit of the slow charger at all times.

5.7.3 Subconclusion

The results show that if a complex charge management strategy is used, charging power is of little concern, as the CMS keeps the actual charging power low and well beneath the peak capacity of the charger. This also shows that in the case of a complex CMS, the use of a fast charger only serves to allow the CMS more flexibility in prioritizing which EVs to charge when.

In the case of simple charge management strategies charging power is very important. As the charging power increases, the charging duration decreases, which produces short load peaks with high amplitudes. This effect is seen very clearly with the timer based charging profile, as well as its substantially negative effect on reinforcement requirements and costs.

6 Perspectives

Charge Management Strategy

The study showed that controlling the charging process has a great impact on reinforcement costs, but control loops are a very complex subject. While it can be of great benefit to the grid to control the charging of EVs, the results have shown that one must tread carefully when employing different forms of control. Simple forms of control, such as timer based charging are easy and inexpensive to implement, but can introduce severe issues in the form of kickback if they are not implemented in a correct manner. Complex forms of control, like load dependent charging present an entirely different set of challenges. They are difficult and expensive to implement, and require detailed and reliable information of future events in order to ensure that all EVs are fully charged when they are needed. This kind of control requires a suitable monitoring of the network and assets and an effective way to perform the appropriate control actions. Additionally, the more general effect of introducing more control loops into the grid must be considered. As the number of control loops grows, so does the overall complexity and the risk of different control loops affecting each other or the overall system negatively. Furthermore, it complicates the work of grid planers, as the interactions of different grid elements can become more difficult to understand.

In order to control EV charging, some form of measurements and communication with the EVs is necessary. The requirements for both depend on what sort of charge management strategy will be used. When evaluating the economic impact of different charge management strategies and their associated charging profiles, one must remember the investments that must be made to facilitate the different charge management strategies and the OPEX required to operate them. Whether controlling EV charging is cheaper than reinforcing can only be answered by considering grid reinforcement at a larger scale and multiple voltage levels. Such a larger scale analysis of reinforcement costs will be conducted in WP9.

Voltage issues

Yet another concern is voltage. While the results showed that voltage control can alleviate many of the voltage reinforcements, it also showed that it is not always a suitable option. In some of the networks the thermal limit is exceeded only a few years after the voltage drop limit. In these cases, voltage control would not be a suitable option, as one would need to reinforce the network regardless. The results showed the impact of the physical and electrical location of EVs and the importance of knowing where in the grid an EV is connected when evaluating voltages. However there is currently no way for DSOs to obtain such information.

Load Balance

Another condition that one must consider is load balance. In this study all loads, including EVs, were balanced three phase loads. Home chargers for EVs today are single phase units. Unbalanced load imposes additional stress on the grid, and voltage in particular can be significantly affected. Every single phase load introduced in the grid is a potential increase of unbalance in the grid. For countries where residential premises are supplied with a single phase unbalance should be a bigger concern than in countries where residential premises are supplied with 3 phases. Smart Meters could help to map the load unbalance in the LV grid. Such a mapping would allow for distributing single phase loads more evenly across the phases. For countries where residential premises are supplied with 3 phases, it should be considered whether to connect EVs to the grid using single phase chargers or three phase chargers, and what benefits can be obtained from the use of three phase chargers.

Distributed Generation

While distributed generation was not considered in this study, it will be necessary to consider the above mentioned topics for distributed generation as well. Distributed generation greatly affects voltage and load balance conditions on LV feeders and will likely move reinforcements ahead. A control strategy for distributed generation must be developed in order to integrate distributed generation in an effective manner.

Future Work

While the results of this study showed the economic impact of different parameters on low-voltage grid reinforcement, more work needs to be done in order to understand the impact EVs have on the higher voltage levels of the electrical grid.

The results of this study showed that there were cases where conventional low-voltage reinforcement of lines and transformers was not sufficient to accommodate the EVs introduced in the networks, and suggested that reinforcement of the medium voltage grid was likely necessary. Future work should investigate the impact of EVs on the medium voltage grid and the coordination required with the LV network. The medium voltage grid is designed and operated differently than the low-voltage grid, and the costs associated with reinforcement of the medium voltage grid are different than those of low-voltage grids.

A large amount of data was necessary to perform this study. This data was not readily available, and while it was possible to obtain some of the base data directly, other data was estimated based on what was obtainable. Future work should investigate what data is necessary and desirable for studies such as this one. It should be investigated how much of this data is readily available and how it is acquired, but more importantly focus on how to acquire data that is not available. More detailed information of existing load is needed, so load can be estimated more accurately. Such data about load could be obtained with Smart Meters, so that load profiles can be generated in a way similar to what has been done in this study. Data that does not relate directly to the grid should also be considered, as information regarding driving patterns (e.g. time of departure and arrival) is necessary to properly assess EV charging profiles.

As shown in D4.3-B1: *D4.3-B1 Grid Impact studies of electric vehicles_Parameters for Assessment of EVs Impact on LV Grid (Annex 2)*, future work should re-evaluate how different loads are estimated. Simplifications, such as scaling down averages obtained for a large amount of customers, may not be sufficiently good to capture the challenges when dealing with few customers. Similarly, future work should evaluate if the way distributed generation, such as PV, is represented sufficiently well in current grid planning procedures or if new methods are required.

Estimation of load does not only pertain to existing load conditions, but also to future load conditions. While estimation of existing load conditions can be aided by measurements, estimation of future load conditions is more difficult. Good estimation of future load conditions, however, is crucial to the grid planning process, as grid assets have an expected lifetime of up to 40 years. Planning horizons are usually shorter than asset lifetime, so while long term forecasts reaching up to 40 years into the future should not be forgotten, the focus should be on making more accurate and more frequent forecasts on a shorter timescale e.g. 10 years. Long term forecasts are important when evaluating whether the current grid structure and design is suitable for the future e.g. should reinforcement be made at low or medium voltage. If the forecasts are incorrect and the grid has to be reinforced before reaching its designed lifetime, unexpected grid reinforcements are necessary and the economic evaluation that was made during grid planning no longer holds true. Such forecast errors often result in significantly higher costs than what would have been incurred if a more expensive solution had been chosen during the original grid planning. If the forecast has overestimated the future load increase, a too expensive solution would be chosen during grid planning, which would also be an economically non-optimal decision.

For this study, ITRES was the main tool. ITRES was developed as part of GeM T4.3, because there were no tools available that had the necessary functionality. This clearly demonstrates that going forward, new tools are necessary. While the current tools are well suited for conventional grid planning, the onset of EVs and distributed generation is challenging the current methods of evaluation used for grid planning. Furthermore, a transition towards smarter grids, introduces new ways of dealing with load, allowing control of loads. The optimal solution will depend on the economic investment, and current tools are ill suited to compare different solutions based on economic value, especially when the aspect of time is included as well. The future requires new tools to support new ways of evaluating and comparing different solutions to the challenges presented by EVs, distributed generation and other new technologies.

7 Conclusion

The impact of different parameters on low-voltage network reinforcement and reinforcement costs has been investigated. The parameters that were investigated were voltage control, EV location, EV charge management strategy, EV penetration and EV charging power.

It was found that the importance of different parameters depended highly on the topology of the networks. Networks with lengths of more than 400m between secondary substation and farthest customer were generally found to be impacted by voltage issues first. Networks with lengths below 300m were generally found to be impacted by thermal issues first. Networks with thermal issues could be divided into two groups – those that required current (line) reinforcement first and those that required transformer reinforcement first. In the evaluated networks the deciding factor appeared to be the number of customers. Networks with few customers were generally supplied by smaller transformers, thus exceeding the thermal limit of the transformer first. Networks with many customers on the other hand were supplied by larger transformers, exceeding the thermal limit of the lines first.

Voltage control and EV location were found to only have a significant impact in networks with voltage issues, while networks with thermal issues were largely unaffected. For networks with voltage issues, EV location is an important parameter.

EV charge management strategy, penetration and charging power were found to have a profound impact on all networks, both with regards to network reinforcement and reinforcement costs.
The two simple charge management strategies showed a significant impact on network reinforcement and reinforcement costs from both penetration and charging power. Two different charging powers were evaluated – 3.7 kW and 22 kW, corresponding to ordinary home chargers and fast chargers. It was found that use of fast chargers increased network reinforcement and reinforcement costs substantially. EV penetration rates were found to have a high impact on network reinforcement and reinforcement costs as well. With low penetration and home

chargers, the majority of the investigated networks required no reinforcement. With high penetration, a significant increase in both network reinforcement and reinforcement costs was found.
The large influence of both charging power and penetration rate show that good forecasts of these parameters are crucial when evaluating the impact of EVs, as both parameters have a significant influence on both network reinforcement and reinforcement costs.

The complex charge management strategy showed a very limited impact from EV penetration and charging power. In the majority of the networks, no reinforcements were seen regardless of EV penetration and charging power.
This demonstrates that with more complex, i.e. grid friendly, charge management strategies, the other parameters evaluated in this study can become largely insignificant.

The study also revealed a need for new methods of estimating load, which require more detailed information. The new level of information requires new ways and more dedicated efforts to acquire the necessary information, among other things stressing the need for more measurements in the electrical grid. For the purpose of collecting more detailed load information, Smart Meters can provide a great value that supports new methods of estimating load.

Furthermore, a need for new tools was found - tools which can estimate the economic impact of different solutions and tools that allow for more flexibility when it comes to forecasts of load, so that grid planning can include new types of loads.

8 Appendix

8.1 Load Profiles

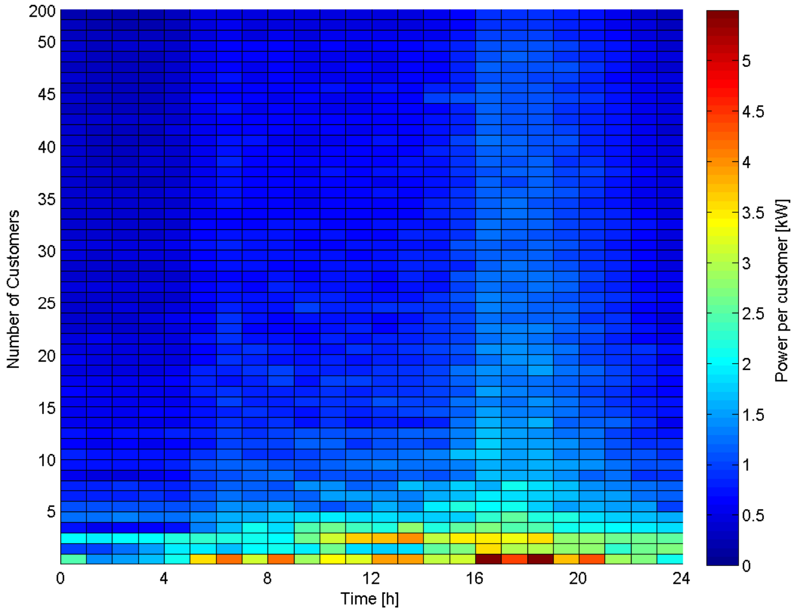

Figure 8.1.1: Load profile set for Danish networks.

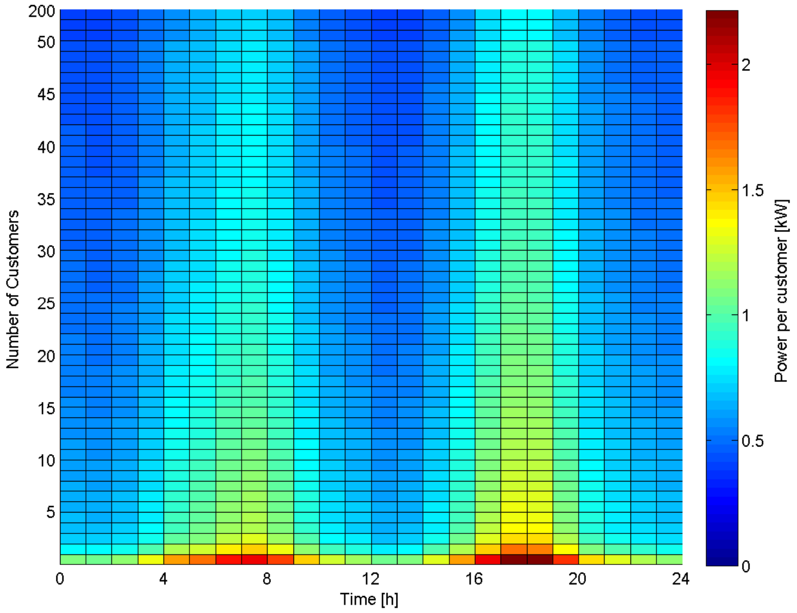

Figure 8.1.2: Load profile set for Italian networks.

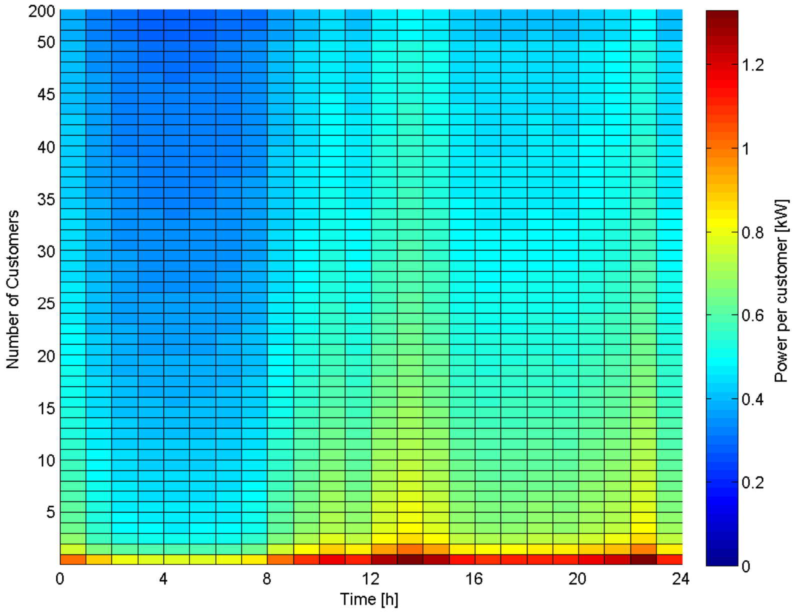

Figure 8.1.3: Load profile set for Spanish networks.

8.2 Charging Profiles

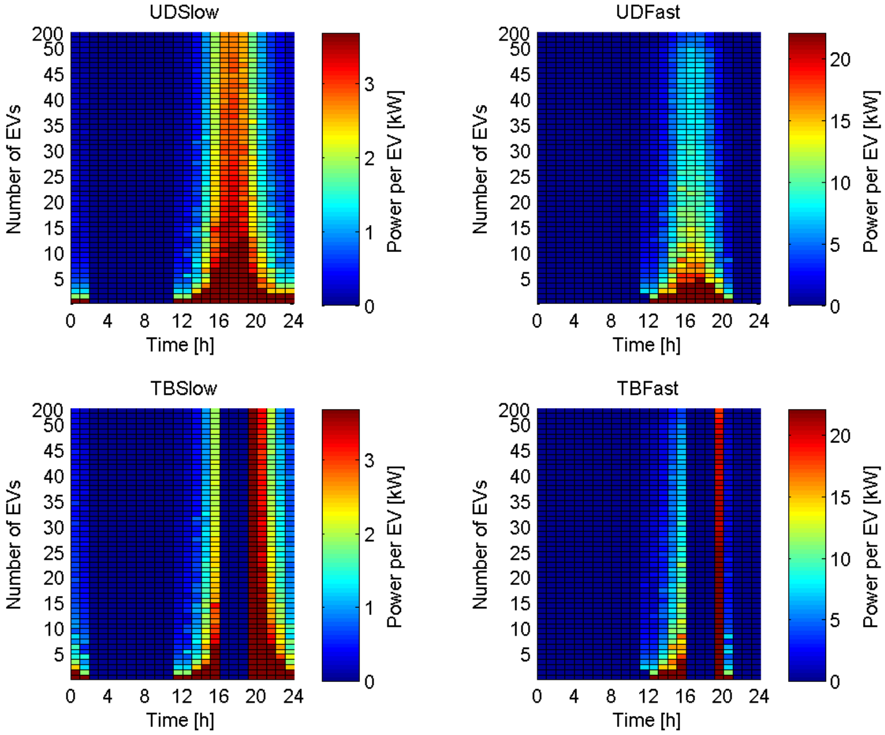

Figure 8.2.1: Charging profile sets for Danish networks for user dependent (UD) and timer based (TB) charging with slow and fast chargers.

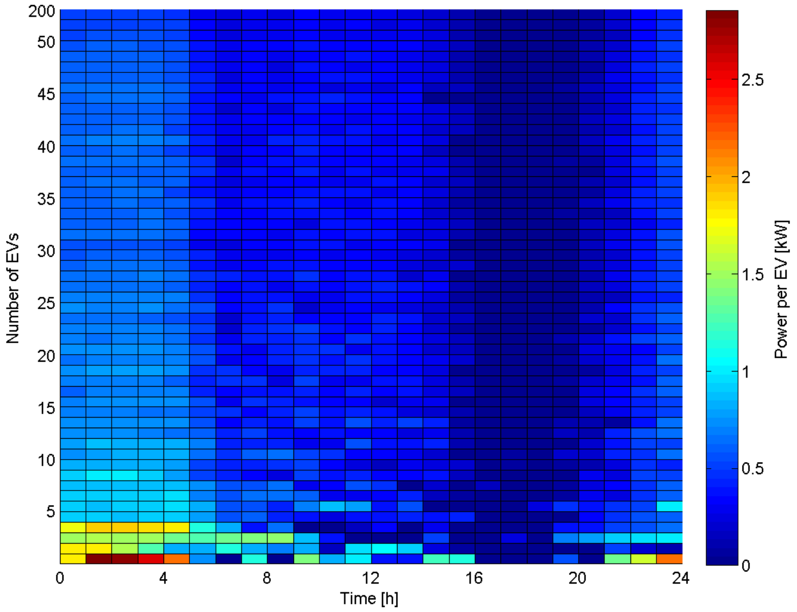

Figure 8.2.2: Charge profile set for Danish networks for load dependent (LD) charging.

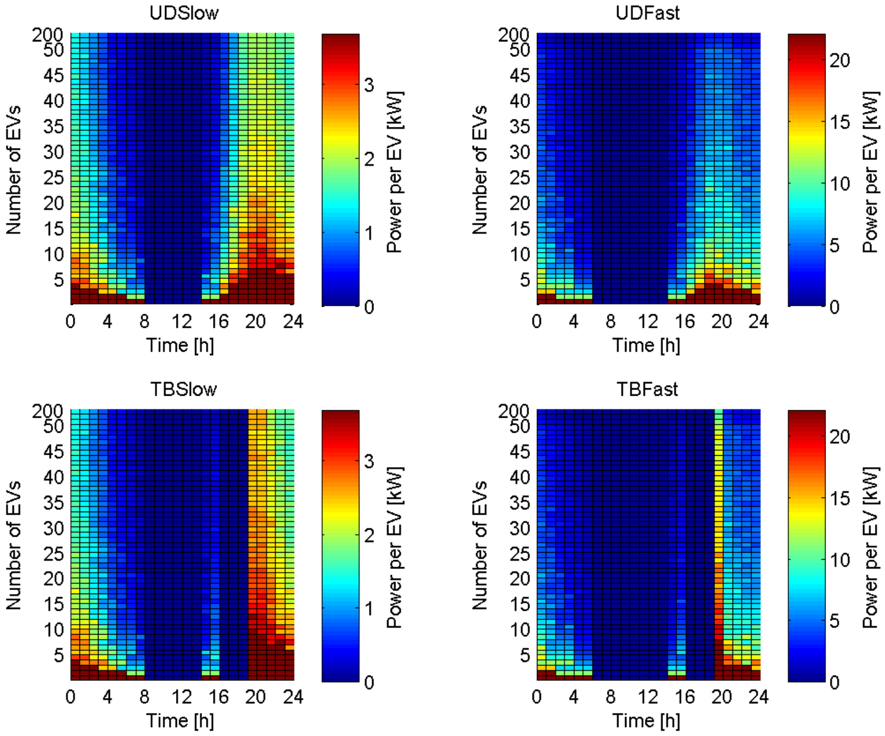

Figure 8.2.3: Charging profile sets for Italian networks for user dependent (UD) and timer based (TB) charging with slow and fast chargers.

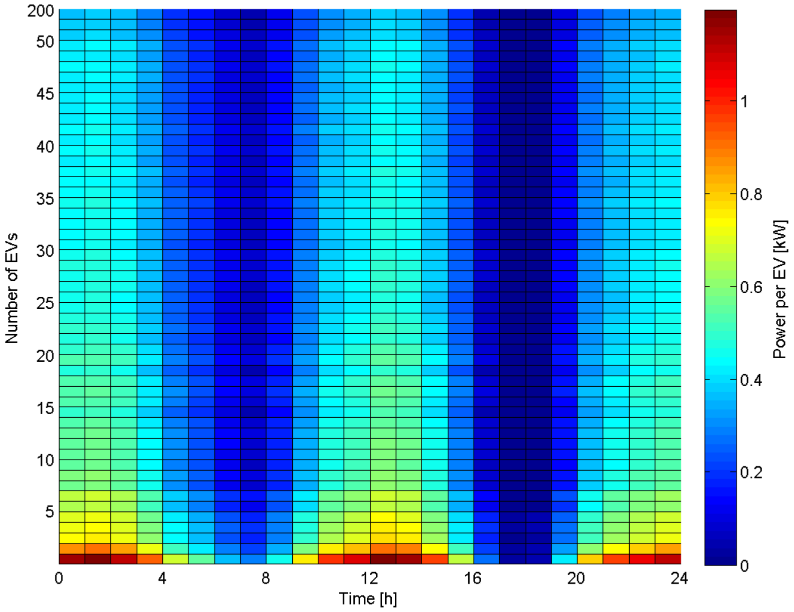

Figure 8.2.4: Charge profile set for Italian networks for load dependent (LD) charging.

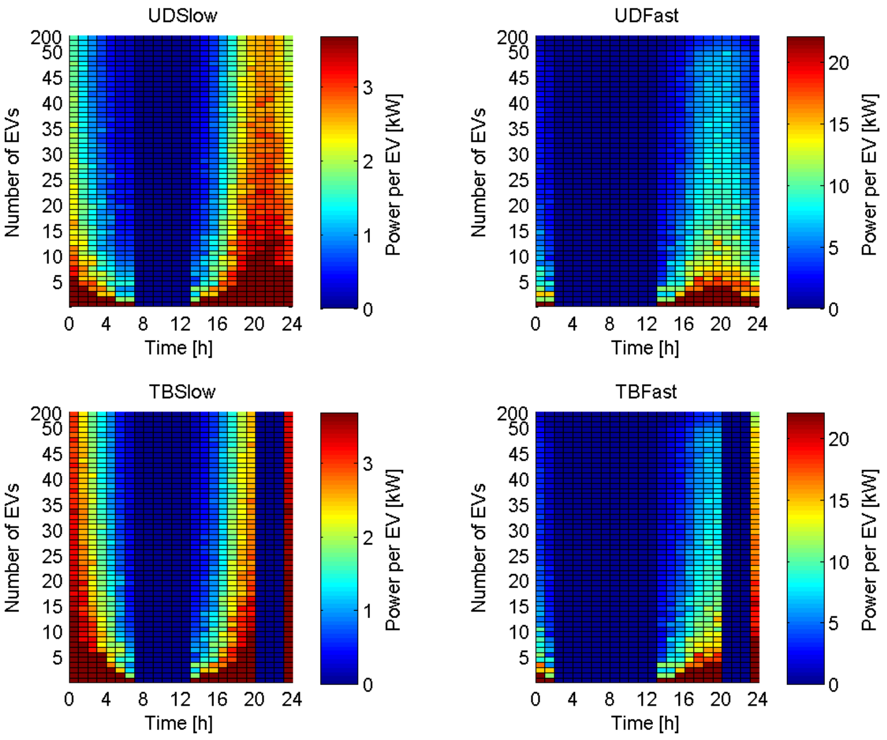

Figure 8.2.5: Charging profile sets for Spanish networks for user dependent (UD) and timer based (TB) charging with slow and fast chargers.

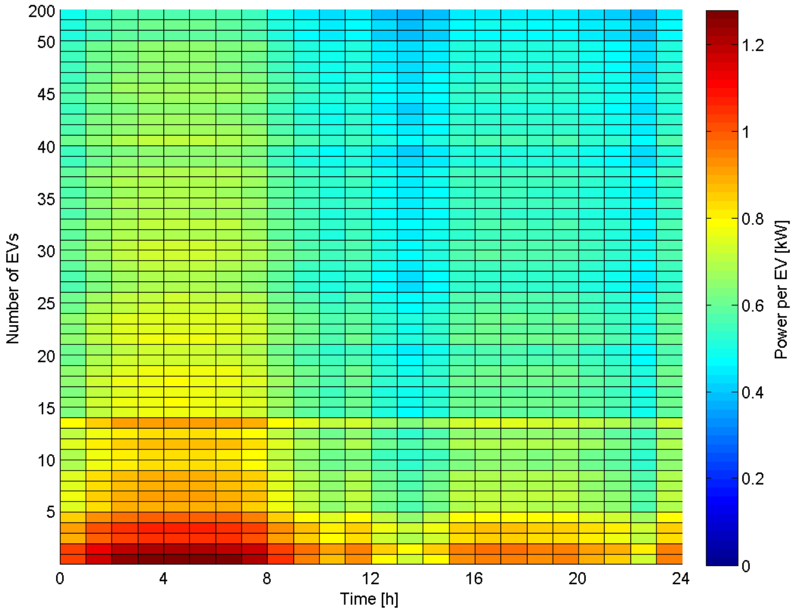

Figure 8.2.6: Charge profile set for Spanish networks for load dependent (LD) charging.

8.3 Economic Results

Network	CAPEX1 (1a)	CAPEX2 (1b)	CAPEX3 (1c)	CAPEX1 – CAPEX2	CAPEX1 – CAPEX3
1	15,474.52	13,641.60	0.00	1,832.92	15,474.52
2	26,695.61	24,213.71	0.00	2,481.91	26,695.61
3	39,844.27	37,356.62	0.00	2,487.65	39,844.27
4	30,363.25	23,181.10	0.00	7,182.15	30,363.25
5	26,427.06	24,954.07	0.00	1,472.99	26,427.06
6	30,833.95	29,056.89	0.00	1,777.06	30,833.95
7	15,102.32	14,095.44	0.00	1,006.88	15,102.32
8	14,757.03	13,385.06	0.00	1,371.97	14,757.03
9	25,778.19	10,723.62	0.00	15,054.57	25,778.19
10	33,314.76	30,598.52	0.00	2,716.24	33,314.76
11	16,291.07	13,402.71	0.00	2,888.37	16,291.07
12	23,528.59	18,198.35	0.00	5,330.24	23,528.59
13	14,072.84	14,072.84	0.00	0.00	14,072.84
14	15,843.67	13,686.36	0.00	2,157.31	15,843.67
15	24,928.22	24,928.22	0.00	0.00	24,928.22
16	20,803.68	20,803.68	0.00	0.00	20,803.68
17	3,337.89	3,068.94	0.00	268.95	3,337.89
18	10,352.81	11,950.81	0.00	-1,597.99	10,352.81
19	16,635.86	16,635.86	0.00	0.00	16,635.86
20	27,953.39	35,699.47	0.00	-7,746.08	27,953.39
21	15,872.58	16,720.06	0.00	-847.48	15,872.58
22	7,992.04	10,854.50	0.00	-2,862.45	7,992.04
23	40,673.07	40,738.27	0.00	-65.20	40,673.07
24	15,843.67	11,822.79	0.00	4,020.88	15,843.67
25	15,089.21	23,077.66	0.00	-7,988.45	15,089.21
26	15,402.23	24,576.64	0.00	-9,174.42	15,402.23
27	19,258.08	14,370.68	0.00	4,887.41	19,258.08
28	10,775.80	18,179.68	0.00	-7,403.88	10,775.80
29	26,810.12	27,524.93	0.00	-714.81	26,810.12
30	103,110.10	121,610.16	40,162.37	-18,500.06	62,947.73
31	15,843.67	13,686.36	0.00	2,157.31	15,843.67
32	30,823.26	30,046.35	0.00	776.91	30,823.26
33	23,408.32	23,408.32	23,408.32	0.00	0.00

Table 8.3.1: Comparison of reinforcement costs in EUR for charging profiles with medium EV penetration (scenarios 1a, 1b and 1c).

Network	Net Value	CAPEX1 (1a)	CAPEX2 (1b)	CAPEX3 (1c)	CAPEX1 – CAPEX2	CAPEX1 – CAPEX3
1	60,369.80	25.6%	22.6%	0.0%	3.0%	25.6%
2	55,860.70	47.8%	43.3%	0.0%	4.4%	47.8%
3	48,450.00	82.2%	77.1%	0.0%	5.1%	82.2%
4	75,085.50	40.4%	30.9%	0.0%	9.6%	40.4%
5	36,075.00	73.3%	69.2%	0.0%	4.1%	73.3%
6	65,175.00	47.3%	44.6%	0.0%	2.7%	47.3%
7	33,400.50	45.2%	42.2%	0.0%	3.0%	45.2%
8	71,873.00	20.5%	18.6%	0.0%	1.9%	20.5%
9	39,053.20	66.0%	27.5%	0.0%	38.5%	66.0%
10	58,064.10	57.4%	52.7%	0.0%	4.7%	57.4%
11	38,613.00	42.2%	34.7%	0.0%	7.5%	42.2%
12	36,930.90	63.7%	49.3%	0.0%	14.4%	63.7%
13	22,982.80	61.2%	61.2%	0.0%	0.0%	61.2%
14	67,865.36	23.3%	20.2%	0.0%	3.2%	23.3%
15	47,124.00	52.9%	52.9%	0.0%	0.0%	52.9%
16	117,356.90	17.7%	17.7%	0.0%	0.0%	17.7%
17	32,325.50	10.3%	9.5%	0.0%	0.8%	10.3%
18	25,933.50	39.9%	46.1%	0.0%	-6.2%	39.9%
19	41,781.75	39.8%	39.8%	0.0%	0.0%	39.8%
20	27,418.50	102.0%	130.2%	0.0%	-28.3%	102.0%
21	35,208.75	45.1%	47.5%	0.0%	-2.4%	45.1%
22	29,112.00	27.5%	37.3%	0.0%	-9.8%	27.5%
23	30,327.60	134.1%	134.3%	0.0%	-0.2%	134.1%
24	18,903.50	83.8%	62.5%	0.0%	21.3%	83.8%
25	36,175.60	41.7%	63.8%	0.0%	-22.1%	41.7%
26	25,991.00	59.3%	94.6%	0.0%	-35.3%	59.3%
27	25,166.90	76.5%	57.1%	0.0%	19.4%	76.5%
28	51,019.70	21.1%	35.6%	0.0%	-14.5%	21.1%
29	35,772.50	74.9%	76.9%	0.0%	-2.0%	74.9%
30	133,988.90	77.0%	90.8%	30.0%	-13.8%	47.0%
31	27,795.60	57.0%	49.2%	0.0%	7.8%	57.0%
32	80,562.80	38.3%	37.3%	0.0%	1.0%	38.3%
33	18,000.00	130.0%	130.0%	130.0%	0.0%	0.0%

Table 8.3.2: Comparison of reinforcement costs in % of network value for charging profiles with medium EV penetration (scenarios 1a, 1b and 1c). Network value is in EUR.

Network	CAPEX1 (1a)	CAPEX2 (2.1)	CAPEX3 (2.2)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	15,474.52	15,474.52		0.00	15,474.52
2	26,695.61	8,822.35		17,873.26	26,695.61
3	39,844.27	26,757.40		13,086.87	39,844.27
4	30,363.25	0.00		30,363.25	30,363.25
5	26,427.06	26,427.06		0.00	26,427.06
6	30,833.95	10,790.29		20,043.66	30,833.95
7	15,102.32	15,102.32		0.00	15,102.32
8	14,757.03	0.00		14,757.03	14,757.03
9	25,778.19	25,778.19		0.00	25,778.19
10	33,314.76	9,726.64		23,588.12	33,314.76
11	16,291.07	16,291.07		0.00	16,291.07
12	23,528.59	15,960.60		7,567.99	23,528.59
13	14,072.84	14,072.84		0.00	14,072.84
14	15,843.67	15,843.67	15,843.67	0.00	0.00
15	24,928.22	24,928.22	24,928.22	0.00	0.00
16	20,803.68	0.00	0.00	20,803.68	20,803.68
17	3,337.89	3,337.89	3,337.89	0.00	0.00
18	10,352.81	10,352.81	10,352.81	0.00	0.00
19	16,635.86	16,635.86	16,635.86	0.00	0.00
20	27,953.39	27,953.39	27,953.39	0.00	0.00
21	15,872.58	15,872.58	15,248.07	0.00	624.51
22	7,992.04	7,992.04	7,992.04	0.00	0.00
23	40,673.07	40,673.07	40,673.07	0.00	0.00
24	15,843.67	15,843.67		0.00	15,843.67
25	15,089.21	15,089.21		0.00	15,089.21
26	15,402.23	15,402.23		0.00	15,402.23
27	19,258.08	19,258.08		0.00	19,258.08
28	10,775.80	10,775.80		0.00	10,775.80
29	26,810.12	26,810.12		0.00	26,810.12
30	103,110.10	83,810.80		19,299.31	103,110.10
31	15,843.67	15,843.67		0.00	15,843.67
32	30,823.26	0.00		30,823.26	30,823.26
33	23,408.32	23,408.32		0.00	23,408.32

Table 8.3.3: Comparison of reinforcement costs in EUR for voltage control (scenarios 1a, 2.1 and 2.2).

Network	Net Value	CAPEX1 (1a)	CAPEX2 (2.1)	CAPEX3 (2.2)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	60,369.80	25.6%	25.6%		0.0%	25.6%
2	55,860.70	47.8%	15.8%		32.0%	47.8%
3	48,450.00	82.2%	55.2%		27.0%	82.2%
4	75,085.50	40.4%	0.0%		40.4%	40.4%
5	36,075.00	73.3%	73.3%		0.0%	73.3%
6	65,175.00	47.3%	16.6%		30.8%	47.3%
7	33,400.50	45.2%	45.2%		0.0%	45.2%
8	71,873.00	20.5%	0.0%		20.5%	20.5%
9	39,053.20	66.0%	66.0%		0.0%	66.0%
10	58,064.10	57.4%	16.8%		40.6%	57.4%
11	38,613.00	42.2%	42.2%		0.0%	42.2%
12	36,930.90	63.7%	43.2%		20.5%	63.7%
13	22,982.80	61.2%	61.2%		0.0%	61.2%
14	67,865.36	23.3%	23.3%	23.3%	0.0%	0.0%
15	47,124.00	52.9%	52.9%	52.9%	0.0%	0.0%
16	117,356.90	17.7%	0.0%	0.0%	17.7%	17.7%
17	32,325.50	10.3%	10.3%	10.3%	0.0%	0.0%
18	25,933.50	39.9%	39.9%	39.9%	0.0%	0.0%
19	41,781.75	39.8%	39.8%	39.8%	0.0%	0.0%
20	27,418.50	102.0%	102.0%	102.0%	0.0%	0.0%
21	35,208.75	45.1%	45.1%	43.3%	0.0%	1.8%
22	29,112.00	27.5%	27.5%	27.5%	0.0%	0.0%
23	30,327.60	134.1%	134.1%	134.1%	0.0%	0.0%
24	18,903.50	83.8%	83.8%		0.0%	83.8%
25	36,175.60	41.7%	41.7%		0.0%	41.7%
26	25,991.00	59.3%	59.3%		0.0%	59.3%
27	25,166.90	76.5%	76.5%		0.0%	76.5%
28	51,019.70	21.1%	21.1%		0.0%	21.1%
29	35,772.50	74.9%	74.9%		0.0%	74.9%
30	133,988.90	77.0%	62.6%		14.4%	77.0%
31	27,795.60	57.0%	57.0%		0.0%	57.0%
32	80,562.80	38.3%	0.0%		38.3%	38.3%
33	18,000.00	130.0%	130.0%		0.0%	130.0%

Table 8.3.4: Comparison of reinforcement costs in % of network value for voltage control (scenarios 1a, 2.1 and 2.2). Network value is in EUR.

Network	CAPEX1 (1a)	CAPEX2 (3.1)	CAPEX3 (3.2)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	15,474.52	15,908.38	13,306.61	-433.86	2,167.90
2	26,695.61	26,695.61	19,478.31	0.00	7,217.31
3	39,844.27	44,517.49	34,449.71	-4,673.22	5,394.56
4	30,363.25	35,735.41	9,855.71	-5,372.16	20,507.54
5	26,427.06	27,511.86	26,427.06	-1,084.80	0.00
6	30,833.95	32,375.65	8,002.13	-1,541.70	22,831.82
7	15,102.32	17,248.92	15,531.58	-2,146.60	-429.27
8	14,757.03	17,354.08	0.00	-2,597.05	14,757.03
9	25,778.19	25,778.19	25,778.19	0.00	0.00
10	33,314.76	41,758.30	21,081.36	-8,443.54	12,233.40
11	16,291.07	16,291.07	16,291.07	0.00	0.00
12	23,528.59	26,875.24	14,567.72	-3,346.65	8,960.88
13	14,072.84	14,072.84	14,072.84	0.00	0.00
14	15,843.67	16,184.18	15,843.67	-340.51	0.00
15	24,928.22	24,928.22	24,928.22	0.00	0.00
16	20,803.68	20,803.68	11,032.64	0.00	9,771.04
17	3,337.89	3,519.06	2,892.88	-181.16	445.01
18	10,352.81	10,352.81	10,352.81	0.00	0.00
19	16,635.86	16,635.86	16,635.86	0.00	0.00
20	27,953.39	27,953.39	27,953.39	0.00	0.00
21	15,872.58	15,872.58	15,248.07	0.00	624.51
22	7,992.04	8,536.06	7,992.04	-544.01	0.00
23	40,673.07	41,436.69	40,673.07	-763.62	0.00
24	15,843.67	15,843.67	15,843.67	0.00	0.00
25	15,089.21	15,089.21	15,089.21	0.00	0.00
26	15,402.23	15,708.96	15,137.48	-306.73	264.74
27	19,258.08	19,258.08	19,258.08	0.00	0.00
28	10,775.80	10,775.80	10,775.80	0.00	0.00
29	26,810.12	26,810.12	18,517.75	0.00	8,292.36
30	103,110.10	123,354.62	82,161.14	-20,244.52	20,948.96
31	15,843.67	15,843.67	15,843.67	0.00	0.00
32	30,823.26	37,744.50	20,959.14	-6,921.24	9,864.12
33	23,408.32	23,408.32	23,408.32	0.00	0.00

Table 8.3.5: Comparison of reinforcement costs in EUR for EV location (scenarios 1a, 3.1 and 3.2).

Network	Net Value	CAPEX1 (1a)	CAPEX2 (3.1)	CAPEX3 (3.2)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	60,369.80	25.6%	26.4%	22.0%	-0.7%	3.6%
2	55,860.70	47.8%	47.8%	34.9%	0.0%	12.9%
3	48,450.00	82.2%	91.9%	71.1%	-9.6%	11.1%
4	75,085.50	40.4%	47.6%	13.1%	-7.2%	27.3%
5	36,075.00	73.3%	76.3%	73.3%	-3.0%	0.0%
6	65,175.00	47.3%	49.7%	12.3%	-2.4%	35.0%
7	33,400.50	45.2%	51.6%	46.5%	-6.4%	-1.3%
8	71,873.00	20.5%	24.1%	0.0%	-3.6%	20.5%
9	39,053.20	66.0%	66.0%	66.0%	0.0%	0.0%
10	58,064.10	57.4%	71.9%	36.3%	-14.5%	21.1%
11	38,613.00	42.2%	42.2%	42.2%	0.0%	0.0%
12	36,930.90	63.7%	72.8%	39.4%	-9.1%	24.3%
13	22,982.80	61.2%	61.2%	61.2%	0.0%	0.0%
14	67,865.36	23.3%	23.8%	23.3%	-0.5%	0.0%
15	47,124.00	52.9%	52.9%	52.9%	0.0%	0.0%
16	117,356.90	17.7%	17.7%	9.4%	0.0%	8.3%
17	32,325.50	10.3%	10.9%	8.9%	-0.6%	1.4%
18	25,933.50	39.9%	39.9%	39.9%	0.0%	0.0%
19	41,781.75	39.8%	39.8%	39.8%	0.0%	0.0%
20	27,418.50	102.0%	102.0%	102.0%	0.0%	0.0%
21	35,208.75	45.1%	45.1%	43.3%	0.0%	1.8%
22	29,112.00	27.5%	29.3%	27.5%	-1.9%	0.0%
23	30,327.60	134.1%	136.6%	134.1%	-2.5%	0.0%
24	18,903.50	83.8%	83.8%	83.8%	0.0%	0.0%
25	36,175.60	41.7%	41.7%	41.7%	0.0%	0.0%
26	25,991.00	59.3%	60.4%	58.2%	-1.2%	1.0%
27	25,166.90	76.5%	76.5%	76.5%	0.0%	0.0%
28	51,019.70	21.1%	21.1%	21.1%	0.0%	0.0%
29	35,772.50	74.9%	74.9%	51.8%	0.0%	23.2%
30	133,988.90	77.0%	92.1%	61.3%	-15.1%	15.6%
31	27,795.60	57.0%	57.0%	57.0%	0.0%	0.0%
32	80,562.80	38.3%	46.9%	26.0%	-8.6%	12.2%
33	18,000.00	130.0%	130.0%	130.0%	0.0%	0.0%

Table 8.3.6: Comparison of reinforcement costs in % of network value for EV location (scenarios 1a, 3.1 and 3.2). Network value is in EUR.

Network	CAPEX1 (4.1a)	CAPEX2 (4.1b)	CAPEX3 (4.1c)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	14,605.24	0.00	0.00	14,605.24	14,605.24
5	0.00	0.00	0.00	0.00	0.00
6	10,127.70	0.00	0.00	10,127.70	10,127.70
7	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00
11	7,107.74	0.00	0.00	7,107.74	7,107.74
12	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00
16	12,771.65	12,771.65	0.00	0.00	12,771.65
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00
26	0.00	0.00	0.00	0.00	0.00
27	11,822.79	0.00	0.00	11,822.79	11,822.79
28	0.00	0.00	0.00	0.00	0.00
29	0.00	0.00	0.00	0.00	0.00
30	51,790.85	47,920.12	40,162.37	3,870.72	11,628.47
31	0.00	0.00	0.00	0.00	0.00
32	11,522.75	7,073.97	0.00	4,448.78	11,522.75
33	23,408.32	23,408.32	23,408.32	0.00	0.00

Table 8.3.7: Comparison of reinforcement costs in EUR for charging profiles with low EV penetration (scenarios 4.1a, 4.1b and 4.1c).

Network	Net Value	CAPEX1 (4.1a)	CAPEX2 (4.1b)	CAPEX3 (4.1c)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	60,369.80	0.0%	0.0%	0.0%	0.0%	0.0%
2	55,860.70	0.0%	0.0%	0.0%	0.0%	0.0%
3	48,450.00	0.0%	0.0%	0.0%	0.0%	0.0%
4	75,085.50	19.5%	0.0%	0.0%	19.5%	19.5%
5	36,075.00	0.0%	0.0%	0.0%	0.0%	0.0%
6	65,175.00	15.5%	0.0%	0.0%	15.5%	15.5%
7	33,400.50	0.0%	0.0%	0.0%	0.0%	0.0%
8	71,873.00	0.0%	0.0%	0.0%	0.0%	0.0%
9	39,053.20	0.0%	0.0%	0.0%	0.0%	0.0%
10	58,064.10	0.0%	0.0%	0.0%	0.0%	0.0%
11	38,613.00	18.4%	0.0%	0.0%	18.4%	18.4%
12	36,930.90	0.0%	0.0%	0.0%	0.0%	0.0%
13	22,982.80	0.0%	0.0%	0.0%	0.0%	0.0%
14	67,865.36	0.0%	0.0%	0.0%	0.0%	0.0%
15	47,124.00	0.0%	0.0%	0.0%	0.0%	0.0%
16	117,356.90	10.9%	10.9%	0.0%	0.0%	10.9%
17	32,325.50	0.0%	0.0%	0.0%	0.0%	0.0%
18	25,933.50	0.0%	0.0%	0.0%	0.0%	0.0%
19	41,781.75	0.0%	0.0%	0.0%	0.0%	0.0%
20	27,418.50	0.0%	0.0%	0.0%	0.0%	0.0%
21	35,208.75	0.0%	0.0%	0.0%	0.0%	0.0%
22	29,112.00	0.0%	0.0%	0.0%	0.0%	0.0%
23	30,327.60	0.0%	0.0%	0.0%	0.0%	0.0%
24	18,903.50	0.0%	0.0%	0.0%	0.0%	0.0%
25	36,175.60	0.0%	0.0%	0.0%	0.0%	0.0%
26	25,991.00	0.0%	0.0%	0.0%	0.0%	0.0%
27	25,166.90	47.0%	0.0%	0.0%	47.0%	47.0%
28	51,019.70	0.0%	0.0%	0.0%	0.0%	0.0%
29	35,772.50	0.0%	0.0%	0.0%	0.0%	0.0%
30	133,988.90	38.7%	35.8%	30.0%	2.9%	8.7%
31	27,795.60	0.0%	0.0%	0.0%	0.0%	0.0%
32	80,562.80	14.3%	8.8%	0.0%	5.5%	14.3%
33	18,000.00	130.0%	130.0%	130.0%	0.0%	0.0%

Table 8.3.8: Comparison of reinforcement costs in % of network value for charging profiles with low EV penetration (scenarios 4.1a, 4.1b and 4.1c). Network value is in EUR.

Network	CAPEX1 (4.2a)	CAPEX2 (4.2b)	CAPEX3 (4.2c)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	33,368.22	35,088.73	0.00	-1,720.50	33,368.22
2	35,756.67	42,760.96	0.00	-7,004.28	35,756.67
3	76,780.98	83,456.84	0.00	-6,675.86	76,780.98
4	58,883.65	72,698.93	0.00	-13,815.27	58,883.65
5	47,840.71	56,663.89	0.00	-8,823.19	47,840.71
6	52,888.18	78,108.09	0.00	-25,219.91	52,888.18
7	26,114.82	25,292.68	0.00	822.14	26,114.82
8	25,045.00	24,546.23	0.00	498.77	25,045.00
9	44,800.79	37,797.17	0.00	7,003.62	44,800.79
10	54,551.08	60,644.71	0.00	-6,093.63	54,551.08
11	24,547.93	23,843.30	0.00	704.63	24,547.93
12	29,700.83	26,488.95	0.00	3,211.88	29,700.83
13	17,105.63	17,105.63	0.00	0.00	17,105.63
14	31,071.76	33,711.73	0.00	-2,639.98	31,071.76
15	43,584.47	42,641.42	7,621.08	943.06	35,963.40
16	22,936.06	22,936.06	0.00	0.00	22,936.06
17	8,040.29	8,905.23	0.00	-864.94	8,040.29
18	27,568.06	29,716.02	0.00	-2,147.96	27,568.06
19	31,509.68	30,370.64	7,621.08	1,139.04	23,888.60
20	63,937.83	81,642.94	0.00	-17,705.10	63,937.83
21	40,169.89	50,904.78	0.00	-10,734.88	40,169.89
22	23,836.03	27,029.30	0.00	-3,193.27	23,836.03
23	73,831.87	96,953.54	0.00	-23,121.67	73,831.87
24	29,395.48	27,690.31	0.00	1,705.18	29,395.48
25	31,848.42	46,905.37	0.00	-15,056.95	31,848.42
26	33,493.09	49,065.27	0.00	-15,572.18	33,493.09
27	32,900.23	29,135.84	0.00	3,764.39	32,900.23
28	33,998.23	47,229.87	0.00	-13,231.64	33,998.23
29	48,226.25	64,973.01	0.00	-16,746.76	48,226.25
30	151,969.49	180,711.95	40,162.37	-28,742.47	111,807.11
31	30,926.27	30,331.83	0.00	594.44	30,926.27
32	39,735.19	48,840.35	0.00	-9,105.16	39,735.19
33	23,408.32	23,408.32	23,408.32	0.00	0.00

Table 8.3.9: Comparison of reinforcement costs in EUR for charging profiles with high EV penetration (scenarios 4.2a, 4.2b and 4.2c).

Network	Net Value	CAPEX1 (4.2a)	CAPEX2 (4.2b)	CAPEX3 (4.2c)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	60,369.80	55.3%	58.1%	0.0%	-2.8%	55.3%
2	55,860.70	64.0%	76.5%	0.0%	-12.5%	64.0%
3	48,450.00	158.5%	172.3%	0.0%	-13.8%	158.5%
4	75,085.50	78.4%	96.8%	0.0%	-18.4%	78.4%
5	36,075.00	132.6%	157.1%	0.0%	-24.5%	132.6%
6	65,175.00	81.1%	119.8%	0.0%	-38.7%	81.1%
7	33,400.50	78.2%	75.7%	0.0%	2.5%	78.2%
8	71,873.00	34.8%	34.2%	0.0%	0.7%	34.8%
9	39,053.20	114.7%	96.8%	0.0%	17.9%	114.7%
10	58,064.10	93.9%	104.4%	0.0%	-10.5%	93.9%
11	38,613.00	63.6%	61.7%	0.0%	1.8%	63.6%
12	36,930.90	80.4%	71.7%	0.0%	8.7%	80.4%
13	22,982.80	74.4%	74.4%	0.0%	0.0%	74.4%
14	67,865.36	45.8%	49.7%	0.0%	-3.9%	45.8%
15	47,124.00	92.5%	90.5%	16.2%	2.0%	76.3%
16	117,356.90	19.5%	19.5%	0.0%	0.0%	19.5%
17	32,325.50	24.9%	27.5%	0.0%	-2.7%	24.9%
18	25,933.50	106.3%	114.6%	0.0%	-8.3%	106.3%
19	41,781.75	75.4%	72.7%	18.2%	2.7%	57.2%
20	27,418.50	233.2%	297.8%	0.0%	-64.6%	233.2%
21	35,208.75	114.1%	144.6%	0.0%	-30.5%	114.1%
22	29,112.00	81.9%	92.8%	0.0%	-11.0%	81.9%
23	30,327.60	243.4%	319.7%	0.0%	-76.2%	243.4%
24	18,903.50	155.5%	146.5%	0.0%	9.0%	155.5%
25	36,175.60	88.0%	129.7%	0.0%	-41.6%	88.0%
26	25,991.00	128.9%	188.8%	0.0%	-59.9%	128.9%
27	25,166.90	130.7%	115.8%	0.0%	15.0%	130.7%
28	51,019.70	66.6%	92.6%	0.0%	-25.9%	66.6%
29	35,772.50	134.8%	181.6%	0.0%	-46.8%	134.8%
30	133,988.90	113.4%	134.9%	30.0%	-21.5%	83.4%
31	27,795.60	111.3%	109.1%	0.0%	2.1%	111.3%
32	80,562.80	49.3%	60.6%	0.0%	-11.3%	49.3%
33	18,000.00	130.0%	130.0%	130.0%	0.0%	0.0%

Table 8.3.10: Comparison of reinforcement costs in % of network value for charging profiles with high EV penetration (scenarios 4.2a, 4.2b and 4.2c). Network value is in EUR.

Network	CAPEX1 (5a)	CAPEX2 (5b)	CAPEX3 (5c)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	81,064.86	123,270.13	0.00	-42,205.26	81,064.86
2	107,574.83	152,591.43	0.00	-45,016.60	107,574.83
3	180,773.53	184,972.88	0.00	-4,199.35	180,773.53
4	128,817.73	220,666.14	0.00	-91,848.41	128,817.73
5	116,436.95	122,002.13	0.00	-5,565.18	116,436.95
6	156,345.46	228,855.39	0.00	-72,509.93	156,345.46
7	85,356.44	101,230.44	0.00	-15,874.00	85,356.44
8	86,579.22	105,248.17	0.00	-18,668.95	86,579.22
9	112,064.48	104,545.74	0.00	7,518.74	112,064.48
10	146,814.49	197,999.96	0.00	-51,185.47	146,814.49
11	60,247.60	70,993.22	0.00	-10,745.63	60,247.60
12	65,007.07	72,855.85	0.00	-7,848.78	65,007.07
13	46,199.76	41,786.94	0.00	4,412.82	46,199.76
14	102,448.04	131,098.53	0.00	-28,650.49	102,448.04
15	108,044.41	109,812.70	0.00	-1,768.28	108,044.41
16	42,589.56	42,589.56	0.00	0.00	42,589.56
17	28,476.96	50,793.95	0.00	-22,316.99	28,476.96
18	62,347.91	108,707.65	0.00	-46,359.74	62,347.91
19	86,954.56	107,915.79	0.00	-20,961.23	86,954.56
20	125,360.94	136,840.93	0.00	-11,480.00	125,360.94
21	92,460.85	126,759.08	0.00	-34,298.22	92,460.85
22	48,742.55	90,326.41	0.00	-41,583.86	48,742.55
23	145,993.29	159,538.90	0.00	-13,545.61	145,993.29
24	65,611.89	78,713.71	0.00	-13,101.82	65,611.89
25	100,820.12	132,121.44	0.00	-31,301.32	100,820.12
26	104,839.16	126,060.02	0.00	-21,220.86	104,839.16
27	83,996.43	83,996.43	0.00	0.00	83,996.43
28	74,399.83	124,943.69	0.00	-50,543.87	74,399.83
29	92,097.17	137,490.25	0.00	-45,393.08	92,097.17
30	208,799.90	281,563.90	40,162.37	-72,764.00	168,637.53
31	102,865.39	111,260.85	0.00	-8,395.46	102,865.39
32	138,402.50	214,075.65	0.00	-75,673.16	138,402.50
33	23,408.32	23,408.32	23,408.32	0.00	0.00

Table 8.3.11: Comparison of reinforcement costs in EUR for charging profiles with fast charging (scenarios 5a, 5b and 5c).

Network	Net Value	CAPEX1 (5a)	CAPEX2 (5b)	CAPEX3 (5c)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	60,369.80	134.3%	204.2%	0.0%	-69.9%	134.3%
2	55,860.70	192.6%	273.2%	0.0%	-80.6%	192.6%
3	48,450.00	373.1%	381.8%	0.0%	-8.7%	373.1%
4	75,085.50	171.6%	293.9%	0.0%	-122.3%	171.6%
5	36,075.00	322.8%	338.2%	0.0%	-15.4%	322.8%
6	65,175.00	239.9%	351.1%	0.0%	-111.3%	239.9%
7	33,400.50	255.6%	303.1%	0.0%	-47.5%	255.6%
8	71,873.00	120.5%	146.4%	0.0%	-26.0%	120.5%
9	39,053.20	287.0%	267.7%	0.0%	19.3%	287.0%
10	58,064.10	252.8%	341.0%	0.0%	-88.2%	252.8%
11	38,613.00	156.0%	183.9%	0.0%	-27.8%	156.0%
12	36,930.90	176.0%	197.3%	0.0%	-21.3%	176.0%
13	22,982.80	201.0%	181.8%	0.0%	19.2%	201.0%
14	67,865.36	151.0%	193.2%	0.0%	-42.2%	151.0%
15	47,124.00	229.3%	233.0%	0.0%	-3.8%	229.3%
16	117,356.90	36.3%	36.3%	0.0%	0.0%	36.3%
17	32,325.50	88.1%	157.1%	0.0%	-69.0%	88.1%
18	25,933.50	240.4%	419.2%	0.0%	-178.8%	240.4%
19	41,781.75	208.1%	258.3%	0.0%	-50.2%	208.1%
20	27,418.50	457.2%	499.1%	0.0%	-41.9%	457.2%
21	35,208.75	262.6%	360.0%	0.0%	-97.4%	262.6%
22	29,112.00	167.4%	310.3%	0.0%	-142.8%	167.4%
23	30,327.60	481.4%	526.1%	0.0%	-44.7%	481.4%
24	18,903.50	347.1%	416.4%	0.0%	-69.3%	347.1%
25	36,175.60	278.7%	365.2%	0.0%	-86.5%	278.7%
26	25,991.00	403.4%	485.0%	0.0%	-81.6%	403.4%
27	25,166.90	333.8%	333.8%	0.0%	0.0%	333.8%
28	51,019.70	145.8%	244.9%	0.0%	-99.1%	145.8%
29	35,772.50	257.5%	384.3%	0.0%	-126.9%	257.5%
30	133,988.90	155.8%	210.1%	30.0%	-54.3%	125.9%
31	27,795.60	370.1%	400.3%	0.0%	-30.2%	370.1%
32	80,562.80	171.8%	265.7%	0.0%	-93.9%	171.8%
33	18,000.00	130.0%	130.0%	130.0%	0.0%	0.0%

Table 8.3.12: Comparison of reinforcement costs in % of network value for charging profiles with fast charging (scenarios 5a, 5b and 5c). Network value is in EUR.

Network	CAPEX1 (1a)	CAPEX2 (4.1a)	CAPEX3 (4.2a)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	15,474.52	0.00	33,368.22	15,474.52	-17,893.71
2	26,695.61	0.00	35,756.67	26,695.61	-9,061.06
3	39,844.27	0.00	76,780.98	39,844.27	-36,936.71
4	30,363.25	14,605.24	58,883.65	15,758.01	-28,520.41
5	26,427.06	0.00	47,840.71	26,427.06	-21,413.64
6	30,833.95	10,127.70	52,888.18	20,706.25	-22,054.22
7	15,102.32	0.00	26,114.82	15,102.32	-11,012.50
8	14,757.03	0.00	25,045.00	14,757.03	-10,287.97
9	25,778.19	0.00	44,800.79	25,778.19	-19,022.61
10	33,314.76	0.00	54,551.08	33,314.76	-21,236.32
11	16,291.07	7,107.74	24,547.93	9,183.33	-8,256.86
12	23,528.59	0.00	29,700.83	23,528.59	-6,172.24
13	14,072.84	0.00	17,105.63	14,072.84	-3,032.79
14	15,843.67	0.00	31,071.76	15,843.67	-15,228.08
15	24,928.22	0.00	43,584.47	24,928.22	-18,656.25
16	20,803.68	12,771.65	22,936.06	8,032.03	-2,132.38
17	3,337.89	0.00	8,040.29	3,337.89	-4,702.40
18	10,352.81	0.00	27,568.06	10,352.81	-17,215.25
19	16,635.86	0.00	31,509.68	16,635.86	-14,873.83
20	27,953.39	0.00	63,937.83	27,953.39	-35,984.44
21	15,872.58	0.00	40,169.89	15,872.58	-24,297.32
22	7,992.04	0.00	23,836.03	7,992.04	-15,843.98
23	40,673.07	0.00	73,831.87	40,673.07	-33,158.81
24	15,843.67	0.00	29,395.48	15,843.67	-13,551.81
25	15,089.21	0.00	31,848.42	15,089.21	-16,759.21
26	15,402.23	0.00	33,493.09	15,402.23	-18,090.86
27	19,258.08	11,822.79	32,900.23	7,435.29	-13,642.14
28	10,775.80	0.00	33,998.23	10,775.80	-23,222.43
29	26,810.12	0.00	48,226.25	26,810.12	-21,416.13
30	103,110.10	51,790.85	151,969.49	51,319.26	-48,859.38
31	15,843.67	0.00	30,926.27	15,843.67	-15,082.60
32	30,823.26	11,522.75	39,735.19	19,300.51	-8,911.93
33	23,408.32	23,408.32	23,408.32	0.00	0.00

Table 8.3.13: Comparison of reinforcement costs in EUR for EV penetration with UD charging (scenarios 1a, 4.1a and 4.2a).

Network	Net Value	CAPEX1 (1a)	CAPEX2 (4.1a)	CAPEX3 (4.2a)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	60,369.80	25.6%	0.0%	55.3%	25.6%	-29.6%
2	55,860.70	47.8%	0.0%	64.0%	47.8%	-16.2%
3	48,450.00	82.2%	0.0%	158.5%	82.2%	-76.2%
4	75,085.50	40.4%	19.5%	78.4%	21.0%	-38.0%
5	36,075.00	73.3%	0.0%	132.6%	73.3%	-59.4%
6	65,175.00	47.3%	15.5%	81.1%	31.8%	-33.8%
7	33,400.50	45.2%	0.0%	78.2%	45.2%	-33.0%
8	71,873.00	20.5%	0.0%	34.8%	20.5%	-14.3%
9	39,053.20	66.0%	0.0%	114.7%	66.0%	-48.7%
10	58,064.10	57.4%	0.0%	93.9%	57.4%	-36.6%
11	38,613.00	42.2%	18.4%	63.6%	23.8%	-21.4%
12	36,930.90	63.7%	0.0%	80.4%	63.7%	-16.7%
13	22,982.80	61.2%	0.0%	74.4%	61.2%	-13.2%
14	67,865.36	23.3%	0.0%	45.8%	23.3%	-22.4%
15	47,124.00	52.9%	0.0%	92.5%	52.9%	-39.6%
16	117,356.90	17.7%	10.9%	19.5%	6.8%	-1.8%
17	32,325.50	10.3%	0.0%	24.9%	10.3%	-14.5%
18	25,933.50	39.9%	0.0%	106.3%	39.9%	-66.4%
19	41,781.75	39.8%	0.0%	75.4%	39.8%	-35.6%
20	27,418.50	102.0%	0.0%	233.2%	102.0%	-131.2%
21	35,208.75	45.1%	0.0%	114.1%	45.1%	-69.0%
22	29,112.00	27.5%	0.0%	81.9%	27.5%	-54.4%
23	30,327.60	134.1%	0.0%	243.4%	134.1%	-109.3%
24	18,903.50	83.8%	0.0%	155.5%	83.8%	-71.7%
25	36,175.60	41.7%	0.0%	88.0%	41.7%	-46.3%
26	25,991.00	59.3%	0.0%	128.9%	59.3%	-69.6%
27	25,166.90	76.5%	47.0%	130.7%	29.5%	-54.2%
28	51,019.70	21.1%	0.0%	66.6%	21.1%	-45.5%
29	35,772.50	74.9%	0.0%	134.8%	74.9%	-59.9%
30	133,988.90	77.0%	38.7%	113.4%	38.3%	-36.5%
31	27,795.60	57.0%	0.0%	111.3%	57.0%	-54.3%
32	80,562.80	38.3%	14.3%	49.3%	24.0%	-11.1%
33	18,000.00	130.0%	130.0%	130.0%	0.0%	0.0%

Table 8.3.14: Comparison of reinforcement costs in % of network value for EV penetration with UD charging (scenarios 1a, 4.1a and 4.2a). Network value is in EUR.

Network	CAPEX1 (1b)	CAPEX2 (4.1b)	CAPEX3 (4.2b)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	13,641.60	0.00	35,088.73	13,641.60	-21,447.13
2	24,213.71	0.00	42,760.96	24,213.71	-18,547.25
3	37,356.62	0.00	83,456.84	37,356.62	-46,100.22
4	23,181.10	0.00	72,698.93	23,181.10	-49,517.83
5	24,954.07	0.00	56,663.89	24,954.07	-31,709.82
6	29,056.89	0.00	78,108.09	29,056.89	-49,051.19
7	14,095.44	0.00	25,292.68	14,095.44	-11,197.25
8	13,385.06	0.00	24,546.23	13,385.06	-11,161.17
9	10,723.62	0.00	37,797.17	10,723.62	-27,073.55
10	30,598.52	0.00	60,644.71	30,598.52	-30,046.19
11	13,402.71	0.00	23,843.30	13,402.71	-10,440.59
12	18,198.35	0.00	26,488.95	18,198.35	-8,290.60
13	14,072.84	0.00	17,105.63	14,072.84	-3,032.79
14	13,686.36	0.00	33,711.73	13,686.36	-20,025.37
15	24,928.22	0.00	42,641.42	24,928.22	-17,713.19
16	20,803.68	12,771.65	22,936.06	8,032.03	-2,132.38
17	3,068.94	0.00	8,905.23	3,068.94	-5,836.29
18	11,950.81	0.00	29,716.02	11,950.81	-17,765.22
19	16,635.86	0.00	30,370.64	16,635.86	-13,734.79
20	35,699.47	0.00	81,642.94	35,699.47	-45,943.46
21	16,720.06	0.00	50,904.78	16,720.06	-34,184.72
22	10,854.50	0.00	27,029.30	10,854.50	-16,174.80
23	40,738.27	0.00	96,953.54	40,738.27	-56,215.27
24	11,822.79	0.00	27,690.31	11,822.79	-15,867.52
25	23,077.66	0.00	46,905.37	23,077.66	-23,827.71
26	24,576.64	0.00	49,065.27	24,576.64	-24,488.62
27	14,370.68	0.00	29,135.84	14,370.68	-14,765.16
28	18,179.68	0.00	47,229.87	18,179.68	-29,050.20
29	27,524.93	0.00	64,973.01	27,524.93	-37,448.08
30	121,610.16	47,920.12	180,711.95	73,690.04	-59,101.79
31	13,686.36	0.00	30,331.83	13,686.36	-16,645.47
32	30,046.35	7,073.97	48,840.35	22,972.38	-18,794.00
33	23,408.32	23,408.32	23,408.32	0.00	0.00

Table 8.3.15: Comparison of reinforcement costs in EUR for EV penetration with TB charging (scenarios 1b, 4.1b and 4.2b).

Network	Net Value	CAPEX1 (1b)	CAPEX2 (4.1b)	CAPEX3 (4.2b)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	60,369.80	22.6%	0.0%	58.1%	22.6%	-35.5%
2	55,860.70	43.3%	0.0%	76.5%	43.3%	-33.2%
3	48,450.00	77.1%	0.0%	172.3%	77.1%	-95.2%
4	75,085.50	30.9%	0.0%	96.8%	30.9%	-65.9%
5	36,075.00	69.2%	0.0%	157.1%	69.2%	-87.9%
6	65,175.00	44.6%	0.0%	119.8%	44.6%	-75.3%
7	33,400.50	42.2%	0.0%	75.7%	42.2%	-33.5%
8	71,873.00	18.6%	0.0%	34.2%	18.6%	-15.5%
9	39,053.20	27.5%	0.0%	96.8%	27.5%	-69.3%
10	58,064.10	52.7%	0.0%	104.4%	52.7%	-51.7%
11	38,613.00	34.7%	0.0%	61.7%	34.7%	-27.0%
12	36,930.90	49.3%	0.0%	71.7%	49.3%	-22.4%
13	22,982.80	61.2%	0.0%	74.4%	61.2%	-13.2%
14	67,865.36	20.2%	0.0%	49.7%	20.2%	-29.5%
15	47,124.00	52.9%	0.0%	90.5%	52.9%	-37.6%
16	117,356.90	17.7%	10.9%	19.5%	6.8%	-1.8%
17	32,325.50	9.5%	0.0%	27.5%	9.5%	-18.1%
18	25,933.50	46.1%	0.0%	114.6%	46.1%	-68.5%
19	41,781.75	39.8%	0.0%	72.7%	39.8%	-32.9%
20	27,418.50	130.2%	0.0%	297.8%	130.2%	-167.6%
21	35,208.75	47.5%	0.0%	144.6%	47.5%	-97.1%
22	29,112.00	37.3%	0.0%	92.8%	37.3%	-55.6%
23	30,327.60	134.3%	0.0%	319.7%	134.3%	-185.4%
24	18,903.50	62.5%	0.0%	146.5%	62.5%	-83.9%
25	36,175.60	63.8%	0.0%	129.7%	63.8%	-65.9%
26	25,991.00	94.6%	0.0%	188.8%	94.6%	-94.2%
27	25,166.90	57.1%	0.0%	115.8%	57.1%	-58.7%
28	51,019.70	35.6%	0.0%	92.6%	35.6%	-56.9%
29	35,772.50	76.9%	0.0%	181.6%	76.9%	-104.7%
30	133,988.90	90.8%	35.8%	134.9%	55.0%	-44.1%
31	27,795.60	49.2%	0.0%	109.1%	49.2%	-59.9%
32	80,562.80	37.3%	8.8%	60.6%	28.5%	-23.3%
33	18,000.00	130.0%	130.0%	130.0%	0.0%	0.0%

Table 8.3.16: Comparison of reinforcement costs in % of network value for EV penetration with TB charging (scenarios 1b, 4.1b and 4.2b). Network value is in EUR.

Network	CAPEX1 (1c)	CAPEX2 (4.1c)	CAPEX3 (4.2c)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	7,621.08	0.00	-7,621.08
16	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	7,621.08	0.00	-7,621.08
20	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00
26	0.00	0.00	0.00	0.00	0.00
27	0.00	0.00	0.00	0.00	0.00
28	0.00	0.00	0.00	0.00	0.00
29	0.00	0.00	0.00	0.00	0.00
30	40,162.37	40,162.37	40,162.37	0.00	0.00
31	0.00	0.00	0.00	0.00	0.00
32	0.00	0.00	0.00	0.00	0.00
33	23,408.32	23,408.32	23,408.32	0.00	0.00

Table 8.3.17: Comparison of reinforcement costs in EUR for EV penetration with LD charging (scenarios 1c, 4.1c and 4.2c).

Network	Net Value	CAPEX1 (1c)	CAPEX2 (4.1c)	CAPEX3 (4.2c)	CAPEX1 - CAPEX2	CAPEX1 - CAPEX3
1	60,369.80	0.0%	0.0%	0.0%	0.0%	0.0%
2	55,860.70	0.0%	0.0%	0.0%	0.0%	0.0%
3	48,450.00	0.0%	0.0%	0.0%	0.0%	0.0%
4	75,085.50	0.0%	0.0%	0.0%	0.0%	0.0%
5	36,075.00	0.0%	0.0%	0.0%	0.0%	0.0%
6	65,175.00	0.0%	0.0%	0.0%	0.0%	0.0%
7	33,400.50	0.0%	0.0%	0.0%	0.0%	0.0%
8	71,873.00	0.0%	0.0%	0.0%	0.0%	0.0%
9	39,053.20	0.0%	0.0%	0.0%	0.0%	0.0%
10	58,064.10	0.0%	0.0%	0.0%	0.0%	0.0%
11	38,613.00	0.0%	0.0%	0.0%	0.0%	0.0%
12	36,930.90	0.0%	0.0%	0.0%	0.0%	0.0%
13	22,982.80	0.0%	0.0%	0.0%	0.0%	0.0%
14	67,865.36	0.0%	0.0%	0.0%	0.0%	0.0%
15	47,124.00	0.0%	0.0%	16.2%	0.0%	-16.2%
16	117,356.90	0.0%	0.0%	0.0%	0.0%	0.0%
17	32,325.50	0.0%	0.0%	0.0%	0.0%	0.0%
18	25,933.50	0.0%	0.0%	0.0%	0.0%	0.0%
19	41,781.75	0.0%	0.0%	18.2%	0.0%	-18.2%
20	27,418.50	0.0%	0.0%	0.0%	0.0%	0.0%
21	35,208.75	0.0%	0.0%	0.0%	0.0%	0.0%
22	29,112.00	0.0%	0.0%	0.0%	0.0%	0.0%
23	30,327.60	0.0%	0.0%	0.0%	0.0%	0.0%
24	18,903.50	0.0%	0.0%	0.0%	0.0%	0.0%
25	36,175.60	0.0%	0.0%	0.0%	0.0%	0.0%
26	25,991.00	0.0%	0.0%	0.0%	0.0%	0.0%
27	25,166.90	0.0%	0.0%	0.0%	0.0%	0.0%
28	51,019.70	0.0%	0.0%	0.0%	0.0%	0.0%
29	35,772.50	0.0%	0.0%	0.0%	0.0%	0.0%
30	133,988.90	30.0%	30.0%	30.0%	0.0%	0.0%
31	27,795.60	0.0%	0.0%	0.0%	0.0%	0.0%
32	80,562.80	0.0%	0.0%	0.0%	0.0%	0.0%
33	18,000.00	130.0%	130.0%	130.0%	0.0%	0.0%

Table 8.3.18: Comparison of reinforcement costs in % of network value for EV penetration with LD charging (scenarios 1c, 4.1c and 4.2c). Network value is in EUR.

Network	CAPEX1 (1a)	CAPEX2 (5a)	CAPEX1 - CAPEX2
1	15,474.52	81,064.86	-65,590.35
2	26,695.61	107,574.83	-80,879.22
3	39,844.27	180,773.53	-140,929.26
4	30,363.25	128,817.73	-98,454.48
5	26,427.06	116,436.95	-90,009.88
6	30,833.95	156,345.46	-125,511.50
7	15,102.32	85,356.44	-70,254.12
8	14,757.03	86,579.22	-71,822.20
9	25,778.19	112,064.48	-86,286.29
10	33,314.76	146,814.49	-113,499.73
11	16,291.07	60,247.60	-43,956.53
12	23,528.59	65,007.07	-41,478.48
13	14,072.84	46,199.76	-32,126.92
14	15,843.67	102,448.04	-86,604.37
15	24,928.22	108,044.41	-83,116.19
16	20,803.68	42,589.56	-21,785.88
17	3,337.89	28,476.96	-25,139.07
18	10,352.81	62,347.91	-51,995.10
19	16,635.86	86,954.56	-70,318.71
20	27,953.39	125,360.94	-97,407.55
21	15,872.58	92,460.85	-76,588.27
22	7,992.04	48,742.55	-40,750.50
23	40,673.07	145,993.29	-105,320.23
24	15,843.67	65,611.89	-49,768.22
25	15,089.21	100,820.12	-85,730.91
26	15,402.23	104,839.16	-89,436.94
27	19,258.08	83,996.43	-64,738.34
28	10,775.80	74,399.83	-63,624.03
29	26,810.12	92,097.17	-65,287.05
30	103,110.10	208,799.90	-105,689.80
31	15,843.67	102,865.39	-87,021.71
32	30,823.26	138,402.50	-107,579.24
33	23,408.32	23,408.32	0.00

Table 8.3.19: Comparison of reinforcement costs in EUR for charging power with UD charging (scenarios 1a and 5a).

Network	Net Value	CAPEX1 (1a)	CAPEX2 (5a)	CAPEX1 - CAPEX2
1	60,369.80	25.6%	134.3%	-108.6%
2	55,860.70	47.8%	192.6%	-144.8%
3	48,450.00	82.2%	373.1%	-290.9%
4	75,085.50	40.4%	171.6%	-131.1%
5	36,075.00	73.3%	322.8%	-249.5%
6	65,175.00	47.3%	239.9%	-192.6%
7	33,400.50	45.2%	255.6%	-210.3%
8	71,873.00	20.5%	120.5%	-99.9%
9	39,053.20	66.0%	287.0%	-220.9%
10	58,064.10	57.4%	252.8%	-195.5%
11	38,613.00	42.2%	156.0%	-113.8%
12	36,930.90	63.7%	176.0%	-112.3%
13	22,982.80	61.2%	201.0%	-139.8%
14	67,865.36	23.3%	151.0%	-127.6%
15	47,124.00	52.9%	229.3%	-176.4%
16	117,356.90	17.7%	36.3%	-18.6%
17	32,325.50	10.3%	88.1%	-77.8%
18	25,933.50	39.9%	240.4%	-200.5%
19	41,781.75	39.8%	208.1%	-168.3%
20	27,418.50	102.0%	457.2%	-355.3%
21	35,208.75	45.1%	262.6%	-217.5%
22	29,112.00	27.5%	167.4%	-140.0%
23	30,327.60	134.1%	481.4%	-347.3%
24	18,903.50	83.8%	347.1%	-263.3%
25	36,175.60	41.7%	278.7%	-237.0%
26	25,991.00	59.3%	403.4%	-344.1%
27	25,166.90	76.5%	333.8%	-257.2%
28	51,019.70	21.1%	145.8%	-124.7%
29	35,772.50	74.9%	257.5%	-182.5%
30	133,988.90	77.0%	155.8%	-78.9%
31	27,795.60	57.0%	370.1%	-313.1%
32	80,562.80	38.3%	171.8%	-133.5%
33	18,000.00	130.0%	130.0%	0.0%

Table 8.3.20: Comparison of reinforcement costs in % of network value for charging power with UD charging (scenarios 1a and 5a). Network value is in EUR.

Network	CAPEX1 (1b)	CAPEX2 (5b)	CAPEX1 - CAPEX2
1	13,641.60	123,270.13	-109,628.53
2	24,213.71	152,591.43	-128,377.72
3	37,356.62	184,972.88	-147,616.26
4	23,181.10	220,666.14	-197,485.04
5	24,954.07	122,002.13	-97,048.06
6	29,056.89	228,855.39	-199,798.50
7	14,095.44	101,230.44	-87,135.00
8	13,385.06	105,248.17	-91,863.11
9	10,723.62	104,545.74	-93,822.11
10	30,598.52	197,999.96	-167,401.44
11	13,402.71	70,993.22	-57,590.52
12	18,198.35	72,855.85	-54,657.50
13	14,072.84	41,786.94	-27,714.10
14	13,686.36	131,098.53	-117,412.17
15	24,928.22	109,812.70	-84,884.48
16	20,803.68	42,589.56	-21,785.88
17	3,068.94	50,793.95	-47,725.01
18	11,950.81	108,707.65	-96,756.84
19	16,635.86	107,915.79	-91,279.93
20	35,699.47	136,840.93	-101,141.46
21	16,720.06	126,759.08	-110,039.02
22	10,854.50	90,326.41	-79,471.91
23	40,738.27	159,538.90	-118,800.64
24	11,822.79	78,713.71	-66,890.92
25	23,077.66	132,121.44	-109,043.78
26	24,576.64	126,060.02	-101,483.38
27	14,370.68	83,996.43	-69,625.75
28	18,179.68	124,943.69	-106,764.02
29	27,524.93	137,490.25	-109,965.32
30	121,610.16	281,563.90	-159,953.74
31	13,686.36	111,260.85	-97,574.49
32	30,046.35	214,075.65	-184,029.31
33	23,408.32	23,408.32	0.00

Table 8.3.21: Comparison of reinforcement costs in EUR for charging power with TB charging (scenarios 1b and 5b).

Network	Net Value	CAPEX1 (1b)	CAPEX2 (5b)	CAPEX1 - CAPEX2
1	60,369.80	22.6%	204.2%	-181.6%
2	55,860.70	43.3%	273.2%	-229.8%
3	48,450.00	77.1%	381.8%	-304.7%
4	75,085.50	30.9%	293.9%	-263.0%
5	36,075.00	69.2%	338.2%	-269.0%
6	65,175.00	44.6%	351.1%	-306.6%
7	33,400.50	42.2%	303.1%	-260.9%
8	71,873.00	18.6%	146.4%	-127.8%
9	39,053.20	27.5%	267.7%	-240.2%
10	58,064.10	52.7%	341.0%	-288.3%
11	38,613.00	34.7%	183.9%	-149.1%
12	36,930.90	49.3%	197.3%	-148.0%
13	22,982.80	61.2%	181.8%	-120.6%
14	67,865.36	20.2%	193.2%	-173.0%
15	47,124.00	52.9%	233.0%	-180.1%
16	117,356.90	17.7%	36.3%	-18.6%
17	32,325.50	9.5%	157.1%	-147.6%
18	25,933.50	46.1%	419.2%	-373.1%
19	41,781.75	39.8%	258.3%	-218.5%
20	27,418.50	130.2%	499.1%	-368.9%
21	35,208.75	47.5%	360.0%	-312.5%
22	29,112.00	37.3%	310.3%	-273.0%
23	30,327.60	134.3%	526.1%	-391.7%
24	18,903.50	62.5%	416.4%	-353.9%
25	36,175.60	63.8%	365.2%	-301.4%
26	25,991.00	94.6%	485.0%	-390.5%
27	25,166.90	57.1%	333.8%	-276.7%
28	51,019.70	35.6%	244.9%	-209.3%
29	35,772.50	76.9%	384.3%	-307.4%
30	133,988.90	90.8%	210.1%	-119.4%
31	27,795.60	49.2%	400.3%	-351.0%
32	80,562.80	37.3%	265.7%	-228.4%
33	18,000.00	130.0%	130.0%	0.0%

Table 8.3.22: Comparison of reinforcement costs in % of network value for charging power with TB charging (scenarios 1b and 5b). Network value is in EUR.

Network	CAPEX1 (1c)	CAPEX2 (5c)	CAPEX1 - CAPEX2
1	0.00	0.00	0.00
2	0.00	0.00	0.00
3	0.00	0.00	0.00
4	0.00	0.00	0.00
5	0.00	0.00	0.00
6	0.00	0.00	0.00
7	0.00	0.00	0.00
8	0.00	0.00	0.00
9	0.00	0.00	0.00
10	0.00	0.00	0.00
11	0.00	0.00	0.00
12	0.00	0.00	0.00
13	0.00	0.00	0.00
14	0.00	0.00	0.00
15	0.00	0.00	0.00
16	0.00	0.00	0.00
17	0.00	0.00	0.00
18	0.00	0.00	0.00
19	0.00	0.00	0.00
20	0.00	0.00	0.00
21	0.00	0.00	0.00
22	0.00	0.00	0.00
23	0.00	0.00	0.00
24	0.00	0.00	0.00
25	0.00	0.00	0.00
26	0.00	0.00	0.00
27	0.00	0.00	0.00
28	0.00	0.00	0.00
29	0.00	0.00	0.00
30	40,162.37	40,162.37	0.00
31	0.00	0.00	0.00
32	0.00	0.00	0.00
33	23,408.32	23,408.32	0.00

Table 8.3.23: Comparison of reinforcement costs in EUR for charging power with LD charging (scenarios 1c and 5c).

Network	Net Value	CAPEX1 (1c)	CAPEX2 (5c)	CAPEX1 - CAPEX2
1	60,369.80	0.0%	0.0%	0.0%
2	55,860.70	0.0%	0.0%	0.0%
3	48,450.00	0.0%	0.0%	0.0%
4	75,085.50	0.0%	0.0%	0.0%
5	36,075.00	0.0%	0.0%	0.0%
6	65,175.00	0.0%	0.0%	0.0%
7	33,400.50	0.0%	0.0%	0.0%
8	71,873.00	0.0%	0.0%	0.0%
9	39,053.20	0.0%	0.0%	0.0%
10	58,064.10	0.0%	0.0%	0.0%
11	38,613.00	0.0%	0.0%	0.0%
12	36,930.90	0.0%	0.0%	0.0%
13	22,982.80	0.0%	0.0%	0.0%
14	67,865.36	0.0%	0.0%	0.0%
15	47,124.00	0.0%	0.0%	0.0%
16	117,356.90	0.0%	0.0%	0.0%
17	32,325.50	0.0%	0.0%	0.0%
18	25,933.50	0.0%	0.0%	0.0%
19	41,781.75	0.0%	0.0%	0.0%
20	27,418.50	0.0%	0.0%	0.0%
21	35,208.75	0.0%	0.0%	0.0%
22	29,112.00	0.0%	0.0%	0.0%
23	30,327.60	0.0%	0.0%	0.0%
24	18,903.50	0.0%	0.0%	0.0%
25	36,175.60	0.0%	0.0%	0.0%
26	25,991.00	0.0%	0.0%	0.0%
27	25,166.90	0.0%	0.0%	0.0%
28	51,019.70	0.0%	0.0%	0.0%
29	35,772.50	0.0%	0.0%	0.0%
30	133,988.90	30.0%	30.0%	0.0%
31	27,795.60	0.0%	0.0%	0.0%
32	80,562.80	0.0%	0.0%	0.0%
33	18,000.00	130.0%	130.0%	0.0%

Table 8.3.24: Comparison of reinforcement costs in % of network value for charging power with LD charging (scenarios 1c and 5c). Network value is in EUR.

8.4 Scenarios

Several scenarios were created to investigate the impact of different parameters on reinforcement and reinforcement costs.

The first three scenarios (0a, 0b and 0c) are constructed to evaluate how many EVs the networks can facilitate with three different charging profiles. No load offset is applied and the number of EVs increases linearly from 0% to 100% in the 25 year reinforcement schedule. Slow chargers are used as they are representative of current home chargers. Voltage limits are set to allow 5% voltage drop and EVs are placed according to the distributed profile.

The scenarios 1a, 1b and 1c are constructed to be the baseline for all parameter evaluation. The three scenarios are constructed to reflect the expected EV development. Load offset is then used to shift the reinforcement schedules so the effect of different parameters can be evaluated.
Apart from the charging profile, the three scenarios are identical. Distributed EV location is used, which is not overly pessimistic with regards to the location of the EVs. EV penetration rate is set to medium, which is the expected EV penetration according to current forecasts (when the startup period is ignored). Slow chargers are used as they are representative of current home chargers and most likely also future home chargers. A maximum voltage drop of 5% is allowed, which is not an uncommon value when evaluating and planning LV feeders.

Scenarios 2.1 and 2.2 are constructed to investigate the effect of voltage control. They are based on scenario 1a and vary the voltage settings to allow a larger voltage drop (10% and 15% respectively).

Scenarios 3.1 and 3.2 are constructed to investigate the effect of EV location. They are based on scenario 1a and only vary the EV location. Being a worst case and a best case, they are corner cases that set the boundaries which all other cases lie within.

Scenarios 4.1 and 4.2 are constructed to investigate the effect of EV penetration. They mirror the baseline scenarios 1a to 1c, and only modify the EV penetration rate. 4.1a to 4.1c use a low penetration rate and 4.2a to 4.2c use a high penetration rate. They thus represent a slow than expected and a faster than expected EV penetration.

Scenarios 5a to 5c are constructed to investigate the effect of charging power. They mirror the baseline scenarios 1a to 1c, and only modify the charging power.

An overview of all the scenarios is given in Table 8.4.1.

Calculation Scenario	EV Location	EV Penetration	Voltage Settings			EV Charging Profile			EV Charging Power	Offset
			Umin	Umax	Uset	User Dependent	Timer Based	Load Dependent		
0a	Distributed	100	0.95	1.1	1	x			Slow	No
0b	Distributed	100	0.95	1.1	1		x		Slow	No
0c	Distributed	100	0.95	1.1	1			x	Slow	No
1a	Distributed	Med	0.95	1.1	1	x			Slow	Yes
1b	Distributed	Med	0.95	1.1	1		x		Slow	Yes
1c	Distributed	Med	0.95	1.1	1			x	Slow	Yes
2.1	Distributed	Med	0.9	1.1	1	x			Slow	Yes
2.2	Distributed	Med	0.9	1.1	1.05	x			Slow	Yes
3.1	Worst case	Med	0.95	1.1	1	x			Slow	Yes
3.2	Best case	Med	0.95	1.1	1	x			Slow	Yes
4.1a	Distributed	Low	0.95	1.1	1	x			Slow	Yes
4.1b	Distributed	Low	0.95	1.1	1		x		Slow	Yes
4.1c	Distributed	Low	0.95	1.1	1			x	Slow	Yes
4.2a	Distributed	High	0.95	1.1	1	x			Slow	Yes
4.2b	Distributed	High	0.95	1.1	1		x		Slow	Yes
4.2c	Distributed	High	0.95	1.1	1			x	Slow	Yes
5a	Distributed	Med	0.95	1.1	1	x			Fast	Yes
5b	Distributed	Med	0.95	1.1	1		x		Fast	Yes
5c	Distributed	Med	0.95	1.1	1			x	Fast	Yes

Table 8.4.1: Overview of calculation scenarios.