technische universität
dortmund

Institute of Energy Systems, Energy
Efficiency and Energy Economics
Prof. Dr.-Ing. C. Rehtanz

**Master's thesis**

# Efficient Use of the Existing Real Estate Infrastructure for Electric Vehicle Charging

**Pascal Fenner**

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| Supervisor | : | Prof. Dr.-Ing. Christian Rehtanz |
| | | Prof. Dr.-Ing. Pertti Järventausta |
| | | Dr.-Ing. Kalle Rauma |
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# Goals of the thesis

Low power charging of electric vehicles (EV) at large real estates, such as apartment buildings, office complexes, shopping centers, etc. has the possibility to expand the charging infrastructure significantly. But not only larger buildings are of particular importance in this context. For a comprehensive infrastructure, it is necessary to set up appropriate charging points at every residential building.
However, the challenge is that every real estate has a distinct internal low voltage network, where the charging strategy must be adapted. Additionally, charging must be made in a "smart" way in order to avoid overloading. Price is also an important factor when talking about a large number of charging points.

The following questions will therefore be answered within the framework of this master's thesis:

- Which charging potentials result from the installation of low power charging points?

- How can it be realized to illustrate existing potentials to investors and property owners?

- What are the advantages of smart charging strategies? To what extent can they contribute to improve the efficiency of a charging system?

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# Abstract

The intention to reduce $CO_2$ emissions in the transport sector is increasing the importance of the electric vehicle. In this context, the development of a nationwide charging infrastructure also becomes a central aspect. To avoid a cost explosion, efficient charging strategies are therefore of great importance.
In this work, it is analyzed to what extent free line capacities of the existing (building) infrastructure can be used in order to provide new charging stations at low cost. Especially the approach of low power charging plays a central role.
For the analysis, charging processes for different building types are simulated and evaluated using Java-based tools. The influence of different input parameters, such as the average distances traveled, on the quality of service of the charging system is analyzed as well. Despite low capacities a high potential becomes visible. Due to comparatively long parking times of the vehicles, higher penetration rates of electric cars result in satisfying charging results too.The low power charging approach can therefore make an enormous impact on a quick expansion of the charging infrastructure.
An equally large potential becomes visible with the analysis of real low power charging data. The results show that for more than half of the charging events the parking time exceeds the pure charging time. In order to use this potential, two optimization approaches are presented within the scope of the work. Their goal is to minimize the total load of the charging system without changing the state of charge of the battery when the customer returns to the vehicle. It shows that peak loads at some locations can be reduced on a scale of up to 50 percent. By using this large peak shaving potential, further charging stations can be installed without unnecessarily large investments.

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# Nomenclature

## Formula Symbols

| | |
|---|---|
| $arr_{int}$ | Arrival variation interval |
| $Car$ | Charging session |
| $Con_{high,NEDC}$ | Higher energy consumption according to NEDC measurement |
| $Con_{high,real}$ | Higher energy consumption under realistic measuring conditions |
| $Con_{med,NEDC}$ | Medium energy consumption according to NEDC measurement |
| $Con_{med,real}$ | Medium energy consumption under realistic measuring conditions |
| $d$ | Number of day/ repetitions of simulation |
| $D_{day}$ | Average daily driving distance |
| $D_{int}$ | Driving distance variation interval |
| $d_{now}$ | Day of charging session |
| $d_{total}$ | Total days of charging data |
| $dep_{int}$ | Departure variation interval |
| $E_{battery}$ | Amount of energy stored in the battery |
| $E_{cha}$ | Charged energy |
| $E_{req}$ | Required energy of an electric vehicle |
| $energy_{day}$ | Charged amount of energy of a vehicle on a particular day |
| $energy_{total}$ | Charged amount of energy of a vehicle during a full charging session |
| $I_{max}$ | Size of the building connection Fuse/ Maximum possible current |
| $\eta$ | Efficiency of battery charging |
| $NoC$ | Number of charging stations/ cars |
| $NoCc$ | Number of cars charging |
| $P_{char,max}$ | Maximum capacity power of an electric vehicle |
| $P_{available}$ | Available free capacity of a building at all times of a day |
| $P_{av,car}$ | Available power per car |
| $P_{max}$ | Maximum capacity of a building connection |
| $P_{peak}$ | Peak load of building |
| $P_{total}$ | Aggregated charging power |
| $power_{ind.opt.}$ | Optimized charging power (individual optimization) |
| $power_{new}$ | Adjusted charging capacity due to rounded charging times |
| $power_{max}$ | Original maximal charging capacity |

| | |
|---|---|
| $R$ | Random value from the interval 0 and 1 |
| $R_{med}$ | Battery range under normal consumption values |
| $s$ | Current charging session |
| $s_{total}$ | Total charging sessions |
| $t$ | Charging time |
| $t_0$ | Start time of simulation |
| $t_{arr}$ | Average time of arrival |
| $t_{day}$ | Daytime in minutes |
| $t_{dep}$ | Average time of departure |
| $t_{end}$ | End time of simulation |
| $t_{max}$ | Time between the first car arrives and the last car leaves |
| $t_{new}$ | Charging/ parking time rounded to 15 minutes value |
| $t_{orig}$ | Original charging/ parking |
| $time_{parking,day}$ | Duration of the parking session on a particular day |
| $time_{parking,total}$ | Duration of the entire parking session |
| $QoS$ | Quality of service |
| $X_{completed}$ | Number of completed charging processes |
| $X_{total}$ | Number of simulated charging processes |

## Abbreviations

| | |
|---|---|
| **AC** | Alternating Current |
| **ADAC** | Allgemeine Deutsche Automobil-Club e.V. |
| **AG** | Aktien Gesellschaft |
| **BDEW** | Bundesverband der Energie- und Wasserwirtschaft e.V |
| **BEV** | Battery Electric Vehicle |
| **CCS** | Combined Charging System |
| **CEE** | Commission internationale de réglementation en vue de l’approbation de l’équipement électrique |
| **CEO** | Chief Executive Officer |
| **DC** | Direct Current |
| **EU** | European Union |
| **EV** | Electric Vehicle |
| **HEV** | Hybrid Electric Vehicle |
| **HVDC** | High Voltage Direct Current |
| **ICCB** | In-Cable Control-Box |
| **IT** | Information Technology |
| **MessEG** | Mess- und Eichgesetz |
| **MessEV** | Mess- und Eichverordnung |
| **NEDC** | New European Driving Cycle |
| **OCPP** | Open Charge Point Protocol |
| **PAngV** | Preisangabenverordnung |
| **PHEV** | Plug-in Hybrid Electric Vehicle |

**PTB** Physikalisch-Technische Bundesanstalt

**QoS** Quality of Service

**SoC** State of Charge

**WLTC** Worldwide harmonized Light Duty Test Cycle

**WLTP** Worldwide Harmonized Light Vehicles Test Procedure

# 1. Introduction

The increasing electrification of road traffic, especially of the automobile, confronts the existing infrastructure with enormous challenges. On the one hand, a nationwide network of charging points must be set up quickly so that the changes in the transport sector are not slowed down. On the other hand, it is in the interest of the population to keep costs at an appropriate level. In the context of this work, the focus will be on charging Electric Vehicle (EV)s with relatively low charging power. The aim of this approach is to use free capacities of the existing network infrastructure as efficiently as possible. In this context, the fear that low charging power leads to insufficient charging level of batteries is of great importance. The quality of service of a charging system therefore represents a central point in the further progress of the work. Based on historical low power charging sessions, a further step will be to determine how the efficiency of the charging system can be further increased through knowledge of individual user behavior.

## 1.1. The Motivation of the Thesis

The subject of climate change is becoming more and more important. More extreme climatic conditions and excessive levels of particulate matter in city centers have become an almost normal part of the daily news. Manipulated exhaust software and the enforcement of diesel driving bans are also part of the everyday life. Targets of the Federal Republic of Germany to reduce greenhouse gas emissions by at least 40 percent by the year 2020 compared to 1990 are far from being achieved. Possible health risks are often of minor importance. However, major global movements such as "Fridays For Future" are now forcing political parties to consider the issue more closely. In particular, the topic of electric mobility is gaining in importance. By charging energy generated from renewable sources, emissions can be reduced and air quality improved [1]. But not only within the framework of $CO_2$ emissions electric mobility can make a difference. Due to the growing share of renewable energies, the energy grid is confronted with increasing challenges [2]. Fluctuating supply makes energy storage technologies an increasingly important topic. In this context, it is conceivable that the batteries of electric vehicles can be used to contribute to grid

stability within the framework of demand-side management [3].
For the integration of EVs, the charging infrastructure is an essential factor. Taking a look at the development of HVDC lines [4] or the expansion of the broadband network [5] in Germany it can be seen that infrastructure projects are associated with long implementation phases and high costs. However, in order to ensure that an accelerated expansion can take place, solutions must be considered that can be integrated into the existing infrastructure. On the one hand, the installation costs should not exceed a certain level, on the other hand, line limitations must be kept in mind. The installation of charging points with low charging power represents an interesting solution in this context. Compared to high power charging, the network load is considerably lower. By using existing infrastructure such as the cables of street lights, low-cost charging points can also be set up. As the proportion of EVs increases, intelligent charging systems are becoming of particular interest in large cities [6]-[7]. By shifting the load of single charging sessions, peak loads can be reduced and energy costs minimized [7]-[8]. Of course the charging time increases due to a lower charging capacity. Apart from commercially used cars like taxis, there are only a few vehicles that drive very long distances every day. Instead, vehicles are parked at home on average for more than 20 hours per day [9]. The danger of an empty battery is therefore not caused by low charging performance but much more by non-existent charging infrastructure. By implementing a resource-saving approach, the acceptance of EVs among the population can also be increased.

## 1.2. The Structure of the Thesis

The present work is divided into a total of eight chapters. In the following, a short overview of the contents of the individual chapters is given.

**Chapter 1** contains the motivation and purpose of the work as well as an overview of the further structure.

In **Chapter 2** an overview of general charging infrastructure standards is given. Based on this, the current situation in Germany is discussed in more detail. Therefore, the current charging network as well as the expansion plans and funding programs become an important aspect. Regulatory requirements, which are sometimes seen as a barrier for faster roll-outs, are also taken into account. In a further step, EVs will also be discussed in more detail. Both technical data and their share of the overall vehicle market will be described.

**Chapter 3** describes the approach of low power charging in more detail. Advantages and disadvantages are discussed and existing concepts are presented.

By developing two different tools, **Chapter 4** describes the potentials of low power charging in more detail. The purpose of the tool is to analyze charging potentials at resident buildings. In particular, it provides a quick overview for investors and property owners whether an investment proves to be an attractive choice.

**Chapter 5** finally deals with the analysis of historical charging data. In a first step, the processing of the data is described and flexibility potentials of the charging data are determined. In a further step, two concepts are presented which aim to reduce peak loads by using the flexibility potentials. By optimizing the data, a more efficient use of infrastructure is to be achieved.

The results in **Chapter 6** presents both the potentials of low power charging (see Chapter 4) and the evaluation of the historical charging data (see Chapter 5). Peak load reductions, which are possible through the optimization approaches, can also be read out depending on the respective location.

Based on the results of the chapters above, an analysis and evaluation of the results takes place in **Chapter 7**. In addition, a comparison of the presented optimization methods takes place.

Finally, **Chapter 8** contains a summary of the work. In addition, future enlargement approaches are briefly discussed.

# 2. State of the Art

The integration of the electric vehicle into the existing transportation system has many challenges. A shorter range and longer charging times compared to conventional combustion engines are only one aspect. Equally important are different standards for charging equipment and the integration of additional loads into the existing power grid. Billing models, as well as data protection guidelines, which are specified by the legislator often represent further barriers to a quick integration of new technologies.
This section first presents general standards for the charging infrastructure and describes the current situation in Germany in more detail. Therefore, both the objectives and funding programs as well as regulatory requirements are explained. In a second step, the focus will shift to vehicles and their users. On the one hand, the current technical standard of electric cars will be presented on the basis of selected vehicles. On the other hand, average driving distances are presented based on a mobility study. In this context, the development of EVs and the goals of the German government are also of great importance.

## 2.1. Standards for Charging Infrastructures

Charging an EV can be done in different ways. In addition to the classic method of charging the battery by cable, there are also inductive approaches on the market.

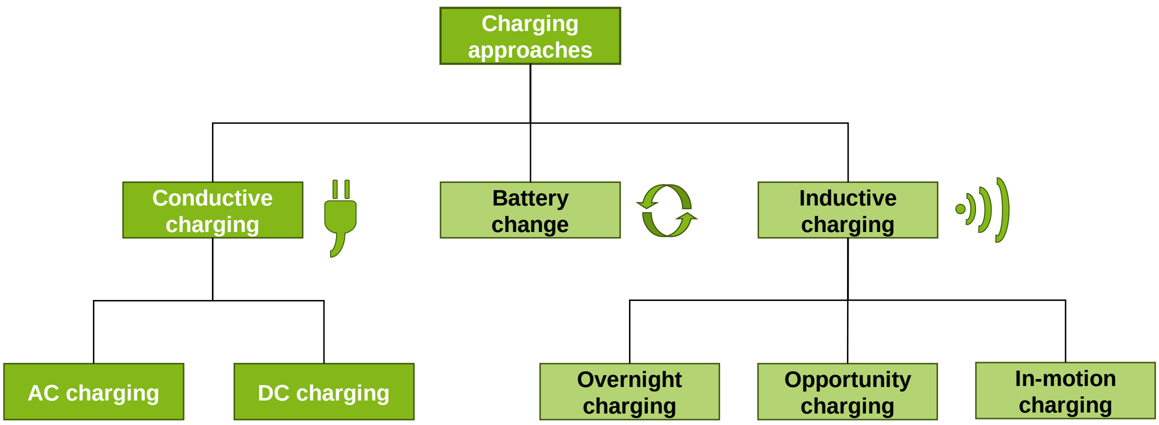



**Figure 2.1:** Different approaches for charging the battery of an electric vehicle

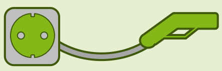
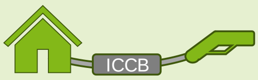
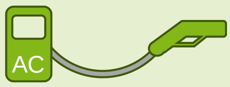
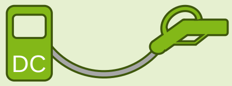
Since 2014 there has been a pilot project in the city of Braunschweig that enables inductive charging for city buses [10]. At selected bus stops, high voltage charging systems are installed under the ground and thus enable continuous use of the buses (opportunity charging). For private customers, too, the first systems have been on the market since 2018. For example, the car manufacturer BMW offers a wireless charging system for its 5 Series [11]. Customers can install this in their garage and thus charge their batteries wirelessly (overnight charging). In the future, it will also be possible to imagine in-motion charging systems that enable charging while driving. In South Korea first test tracks for buses are already in use [12]. However, it remains to be seen whether the high investment costs for the infrastructure can be reconciled with the resulting benefits.
A further conceivable variant of the recharging process represents the exchange of the battery. To achieve this, however, a battery standardization for all manufacturers would have to be provided. In addition, the battery must be easy to reach, so that a change could take place in a few minutes.
In this thesis, the focus will be on conductive charging, which is likely to be the dominant technology in the coming years.
Generally, a distinction is made between Direct Current (DC) and Alternating Current (AC) charging approaches, which are explained in more detail below.

### 2.1.1. AC Charging

AC charging is the most widespread charging method in Germany today. Due to the fact that batteries require direct current for charging, this charging method requires a rectifier. By default, these are already installed in the vehicle via an onboard charger. However, higher performance of the onboard chargers are usually associated with higher costs and weight increases, which is why the AC charging performance is limited at this point [13].
However, the charging speed of the battery also depends on other components. If, for example, the car is supplied with single-phase power via a Schuko or CEE plug (charging mode 1), the maximum charging power is 3.7 kW (16 A, 230 V). Due to the fact that most Schuko plugs are not designed for continuous operation at 16 A, current is typically limited to 10 A (2.3 kW) [14]. As shown in Table 2.1, there is no communication between the vehicle and the power source. This means that the

socket must be protected with a residual current circuit breaker [15].
Charging mode 2 differs from the above mentioned method by an In-Cable Control-Box (ICCB) integrated in the charging cable. The charging current can be adjusted according to the situation by using a pulse width modulated controlled pilot signal. By using a three-phase connected CEE plug, charging capacities of up to 22 kW can be achieved [13], [15].

**Table 2.1:** Four different charging modes for charging electric vehicles [15]

| Mode 1 | Mode 2 | Mode 3 | Mode 4 |
|---|---|---|---|
|  |   |   |   |
| • Single-phase<br>• Up to 3,7 kW (Schuko)<br>• No communication<br>• Residual current circuit breaker necessary | • Single- and three-phase<br>• Up to 22 kW (3-phases)<br>• Communication between In-Cable Control-Box and onboard charger | • Three-phase<br>• Up to 43.5 kW<br>• Communication between charging station and onboard charger | • DC charging<br>• Up to 400 kW<br>• Communication between charging station and vehicle |

Charging power of up to 43.5 kW can be achieved in charging mode 3. The charging cable is either permanently installed in the charging station or connected via the type 2 connector shown in Table 2.2. Similar to charging mode 2, communication between the charging station and the onboard charger takes place via a pulse width controlled pilot signal.

According to the charging post ordinance ("Ladesäulenverordnung") of March 9th, 2016, for reasons of interoperability every charging point in Germany must be equipped at least with sockets or with sockets and vehicle couplings of type 2 in accordance with the standard DIN EN 62196-2. In the case of older vehicles and charging points, other plug types may occasionally be found. However, the EU Directive 2014/94/EU of October 22nd, 2014 on the deployment of alternative fuels infrastructure stipulates that type 2 plugs should become the standard in Europe.

**Table 2.2:** Region-specific and current-dependent charging plug types [16]

| | Type 1 / USA, Japan | Type 2 / Europa | GB / China |
|---|---|---|---|
| AC charging |  SAE J1772 / IEC 62196-2 |  IEC 62196-2 |  GB Part 2 |
| DC charging |  IEC 62196-3 |  IEC 62196-3 |  GB Part 3 / IEC 62196-3 |
| Combined AC/DC charging system |  SAE J1772 / IEC 62196-3 |  IEC 62196-3 | |

As Table 2.2 shows, a globally uniform standard is not realistic in the near future. Vehicles from European manufacturers who want to sell their products in the United States, for example, must therefore install other connector systems on these vehicles.

In addition to charging with alternating current, direct current charging techniques are also available. Positive and negative effects are briefly discussed below.

### 2.1.2. DC Charging

Germans are still skeptical about electro-mobility. Concerns regarding the short range and long charging times frighten many people away from switching to an EV [17]. In order to reduce charging times, DC charging stations are increasingly being installed. The great advantage of DC charging is that the charging process is independent of the installed onboard charger. The result is higher charging performance which results in shorter charging times [18].
DC charging is also referred to charging mode 4 and is standardized in Europe via the Combined Charging System (CCS) plug see Table 2.2 (charging post ordinance ("Ladesäulenverordnung") of March 9$^{th}$, 2016). Most DC charging points today offer 50 kW power. The new "V3 Supercharging" system of the manufacturer Tesla

which was introduced in March 2019 can already provide charging capacities of up to 250 kW [19]. Also a 400 kW offer is to be classified as realistic in the future [20]. A major disadvantage of charging with direct current is the high load on the power grid [21]. Cost-intensive investments in the power grid or in storage systems are therefore often necessary [14]. However, especially at highway service stations the construction of further DC charging points seems to be inevitable. When driving long distances, drivers are certainly not willing to take breaks longer than the usual coffee break of 10-20 minutes.

In the following section, the infrastructure in Germany and the expansion goals of the German government will be discussed in more detail.

## 2.2. Infrastructure in Germany

Electric mobility is attracting increasing attention in Germany due to the threat of driving bans for many diesel vehicles. Nevertheless, the integration of electric vehicles into everyday road traffic is largely dependent on the provided charging infrastructure. Even if it sounds relatively easy to switch to an electric vehicle, availability and proximity to the nearest charging point are important factors. No driver will be thrilled if the next charging station is located hundreds of meters away from home, especially if it is already occupied by other cars.

### 2.2.1. Charging Points

In principle, a distinction is made between normal and fast charging points when defining charging points. The normal charging point category includes all charging points at which electricity with a maximum charging capacity of 22 kilowatts can be transmitted to an electric vehicle. The charging capacity of the fast charging points is accordingly higher than the 22 kW mentioned above (see charging post ordinance ("Ladesäulenverordnung") of March 9$^{th}$, 2016).
In order to make the EV a serious alternative to conventionally powered vehicles

in the medium term, the Federal Government's coalition agreement (19th legislative period) provides that the expansion of the infrastructure will be promoted. It is specified that by the year 2020 at least 100,000 additional charging points, which contain more than a third of DC fast charging points, are to be created [22]. According to the Federal Association of Energy and Water Management (BDEW), a total of approximately 13,500 (semi-) public charging points were installed in Germany by mid-2018. As can be seen in Figure 2.2, a continuous increase in charging points can be recognized in recent years. However, it remains questionable whether an increase of 700 percent can be implemented within two and a half years. If, for comparison, the change between mid-2015 and the end of 2017 is considered, only an increase of around 100 percent can be observed.

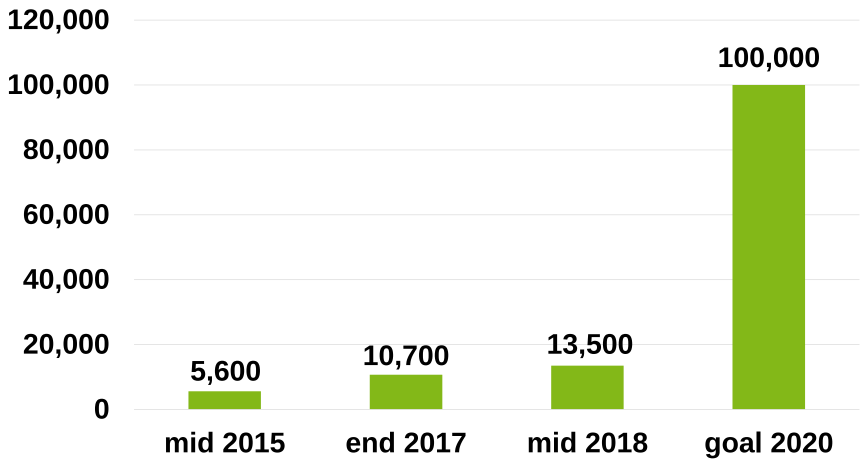



**Figure 2.2:** Development of the charging point infrastructure in Germany including the expansion target of the German Federal Government [22][23][24]

In order to accelerate the expansion of the charging infrastructure in Germany, the Federal Republic of Germany is providing funding packages for making investments more attractive. These are described in more detail in the following section.

### 2.2.2. Government Funding for New Charging Points

Already in 2016, the Federal Cabinet decided on a funding program for public charging points. The funding volume amounts to 300 million euros over the period from 2017 to 2020. The amount of funding depends on the region and the power output. Table 2.3 shows the respective funding potentials that were advertised in the third call for proposals [25]. In this case, the deadline for submitting proposals was February 2019.

**Table 2.3:** Location- and power-dependent fundings for new charging stations in Germany [26]. Blue zones represent areas with a higher need for charging points.

| 3.7 – 22 kW | 50 – 100 kW | | > 100 kW | |
|---|---|---|---|---|
| Max. 40 %<br>And<br>Max. 2,500 € | „Blue-zone“ | „Yellow-zone“ | „Blue-zone“ | „Yellow-zone“ |
| | Max. 50 %<br>And<br>Max. 12,000 € | Max. 30 %<br>And<br>Max. 9,000 € | Max. 50 %<br>And<br>Max. 30,000 € | Max. 30 %<br>And<br>Max. 23,000 € |

In order to benefit from a subsidy, certain conditions must be fulfilled. As already described in Section 2.1, AC charging stations must have type 2 respectively DC charging stations combo 2 connectors. As well a charging station must meet minimum technological requirements regarding authentication and billing systems as well as IT back end and roaming systems. In accordance with the current call, the operator must ensure that a charging station remains in operation for at least six years and is accessible at any time (7 days per week). As a further prerequisite for support, it is mandatory that the electricity supplier obtains its energy from renewable energy producers [26].
Ultimately, the contract is placed by tender, with the central criterion being the lowest funding costs per kilowatt of charging capacity [26]. Of course, there is also an effort to distribute charging stations as area-wide as possible and in line with demand. For this purpose, the territory of the Federal Republic of Germany is divided into 283 zones, which are assigned a certain amount of additional charging points. In the case of fast charging points, a distinction is made between areas with high and low funding requirements (Annex A.1 shows an example of the funding requirements of the City of Dortmund). Areas with a higher funding requirement (blue zones) can apply for higher funding as shown in Table 2.3.

## 2.3. Regulatory Requirements

Legal requirements can have both positive and negative effects on the rapid expansion of the charging infrastructure. On the one hand, many people want laws that prescribe precise and data-protection-compliant billing systems through clear rules. Unfortunately, a slowdown of new innovative solutions often stands in line with this. On the other hand, laws can also accelerate the expansion of charging points. Stricter regulations for new or renovated buildings offer the opportunity to speed up an efficient expansion.
In the following, current and future requirements for charging points will be discussed in more detail. Regulations for the renovation of buildings are presented as well.

### 2.3.1. Billing Rates

When charging an electric vehicle at a public charging station, the question of an appropriate billing model quickly arises. In general different approaches are conceivable and already available on the market.

- One approach is to distribute **electricity for free**. Although the expenses of the operator of the charging station are not directly offset by income, the donation can still be seen as an advertising measure. A grocery store operator could, for example, win new customers by offering free charging and ultimately increase its revenue. With an increasing number of EVs and charging stations, however, it remains questionable whether this model can remain profitable in the long term.
- Another form of invoicing are **time-based models**. Similar to a parking meter, the customer is charged a certain fee per time unit, regardless of how much energy is actually absorbed by the battery. Due to the fact that the charging behavior depends on the State of Charge (SoC) [27] and on the battery properties themselves, it is in a way an unfair approach.
- Fixed rates are also a conceivable option. The customer is only charged a **fixed fee** which is independent of the charging time. It therefore makes no difference whether only 10 or 100 percent of the battery capacity is recharged.

Customers whose vehicles have larger battery capacities are therefore better suited to customers with smaller battery capacities.

- The probably fairest method of billing is the **kilowatt-hours accurate billing**. Regardless of charging speed and charging capacity, the customer only pays for the energy actually received. For a billing model of this type, however, the complexity of the charging system increases, as watt meters have to be installed, among other things.
- The last approach that can be mentioned here is a **flat rate based model**. The customers commit themselves to a supplier for a certain period of time and pay a fixed amount which is independent of the actual consumed energy. Consequently, the customers can refuel their vehicles with electricity at a charging station of the supplier for as long and as often as they want without incurring additional costs.

Basically, it can be said that the various billing models have advantages as well as disadvantages. Therefore, only three of the aforementioned models are legally permitted in Germany. According to § 3 of the Price Indication Ordinance (Preisangabenverordnung (PAngV)), electricity must always be offered with a consumption-dependent value. One kilowatt-hour is to be used as the unit of measure for the working price. A legal opinion [28] issued by the Federal Ministry of Economics and Energy in 2018 confirms that the regulation can also be applied to tariff models for charging current for electric cars. Consequently, both time and fixed tariffs for individual charging processes are not permitted in Germany. The situation is different with the flat rate tariffs. In this case, the legal opinion assumes that these are compatible with the Price Indication Ordinance (PAngV) as long as they cover a period of at least one month (Energy Industry Act § 40 Section 3), ([28]). The consumers know clearly in advance which concrete price they have to pay for which concrete service (unlimited amount of electricity for the agreed period). This means that the principles of price clarity and price accuracy can be ensured.
Since it cannot be assumed that in the future all customers will be equipped with flat rate tariffs or that public charging stations will only provide electricity for free, the installation of kilowatt-hour billing systems in Germany seems to be unavoidable.

In the following section, the concrete implementation of the measuring system is described in more detail and various approaches are briefly presented.

### 2.3.2. Measuring and Calibration Law

In Germany, the Measuring and Calibration Regulation (Mess- und Eichverordnung (MessEV)) and the Measuring and Calibration Law (Mess- und Eichgesetz (MessEG)) lay down the essential requirements for all types of measuring instruments. § 7 Section 1 (MessEV) states, among other things, that measurement results must be protected or secured against counterfeiting, and that they must be testable. Especially the test ability represents a certain challenge in this case, since often, other than at a conventional filling station, it is not possible to pay directly to the gas station attendant. Under certain circumstances, billing may not take place until the end of the month via a service provider in the form of a collected invoice. As a result, a way must be created which makes it possible to check the actually charged energy even after it has been charged (see § 33 MessEG). In Appendix 2 Section 9 of the MessEV, the display of the measurement results is defined in more detail and can be carried out either via a visual display or a printout. Even though the receipt printing seems to be easy to realize in the first place, it must not be neglected that the printer is exposed to weather fluctuations in contrast to a cash register in a grocery store. It should also be noted that the availability of printing paper and ink must be ensured at all times.
If the measured values are displayed on a visual display, this can either be located in the charging station itself or can be read out via a corresponding non-reactive interface. In order to ensure test ability at a later date, measurement data must be stored accordingly and can be recalled at a later date. In addition, it must be ensured that the data is protected against manipulation at all times, especially during transmission to an external medium.

On the market there are currently different approaches regarding the implementation of the MessEG and MessEV, which have been approved by the Physikalisch-Technische Bundesanstalt (PTB) a German federal testing institute. One option, for example, is the so-called SAM solution of the company EBG Compleo. The measured values are stored in the charging station itself and can be recalled at a later time. To do this, however, the user must return to the location of the charging station, which involves a great effort if charging points are further away. An alternative is the public key signature procedure [29]. Here, the measured data are collected by the charging station and transmitted to a back end. Communication takes place via the

Open Charge Point Protocol (OCPP) standard for charging stations [30]. In order to prevent manipulation of the measurement data, the data is encrypted with a digital signature before it is transmitted. Subsequently, the customer can access the data with a time delay using suitable software.

In addition to the billing and storage regulations for charging data mentioned above, further specifications for charging points will come into force from 2021. Requirements for so-called smart meter gateways are dealt with in more detail in the following section.

### 2.3.3. Smart-Meter-Gateway Requirements

In Germany, the minimum technical requirements for a measuring point are specified by the Measuring Point Operating Law (Messstellenbetriebsgesetz). The current version of the law specifies that stricter requirements will come into force for some of the charging points from 2021.
Depending on the installed capacity and the annual electricity consumption, the operator has different duties. According to § 29, operators whose measuring points have an installed capacity of more than 7 kW are required to install intelligent measuring systems in their measuring points. The same applies if the annual consumption of a measuring point exceeds 6 MWh. Section 21 of the law specifies the minimum requirements for an intelligent metering system in more detail. In addition to the reliable collection of measured values and their processing, a further requirement is the remote controllability of the system as well as the secure and efficient remote communication technology. Further, a smart meter gateway must be used to provide a way of prioritizing certain applications, whereby measurements and switching by the network operator must always be prioritized. To ensure data protection, security profiles and technical guidelines are explained in more detail in § 22. It is also specified that a smart metering public key infrastructure must be integrated, which, was already mentioned in Section 2.3.2, to ensure fraud-proof transmission.
According to § 48, measuring systems used exclusively for charging EVs can still make use of a transitional regulation until December 31$^{st}$ 2020.

### 2.3.4. Renovation of Existing Buildings

In order to achieve the climate targets and improve air quality, the European Union (EU) defines basic requirements for the renovation of existing buildings. Electric mobility, which helps to reduce $CO_2$ emissions through an increasing share of renewable energies, plays an important role in this context. To ensure that the integration of electric vehicles is as efficient as possible, certain requirements must be fulfilled when renovating buildings.
EU directive (EU) 2018/844 of May 30$^{th}$ in 2018 amending Directive 2010/31/EU on the energy performance of buildings, which will come into force on 10 March 2020. In general, the Directive distinguishes between non-residential buildings and residential buildings. Article 1, point 5, paragraph 2 of the directive (EU) 2018/844 specifies the requirements for non-residential buildings. If there are more than 10 parking lots in or in the immediate vicinity of the building, at least one charging point must be installed as a part of the renovation. In addition, 20 percent of all parking lots must already have a corresponding infrastructure that enables a quick retrofitting of a charging point. Paragraph 3 adds that by January 2025 a minimum number of charging points will also be specified for car parks with more than 20 spaces. Requirements for residential buildings are described in more detail in paragraph 5. Once again, all buildings with at least 10 parking lots are affected. As part of a renovation, all parking lots must be equipped with an infrastructure that enables quick retrofitting of charging points. However, a minimum number of charging points is not specified. Exceptions for all types of buildings are described in paragraph 6. If the cost of laying empty pipes exceeds the total cost of renovation by more than 7 percent, or if a possible charging system could endanger the stability of the network, it is possible to deviate from this requirement.

## 2.4. Electric Vehicles

Many years before Carl Benz applied for the patent for the first gas-powered car in 1886, the first Electric Vehicle (EV) was developed in 1834 [31]. Even in the beginning of the 20th century it was not yet clear which of the technologies would prevail in the end [32]. However, due to limited battery capacity, a relatively low oil price and the rapid progress of the gasoline engine, the electric car was almost completely

ousted from the market by 1930. As a result of the oil crisis in the 1970s, the EV finally got its second chance [31]. Due to the limited oil resources and a growing interest in lowering emissions from the transport sector, the EV has since regained its importance. Many politicians today see the technology as the technology of the future. Countries such as Sweden and Denmark have already announced their intention to ban combustion engines from 2030.
For today's EV, a distinction has to be made between three types of cars.

- Vehicles whose engines are only powered by electricity from their batteries are called **Battery Electric Vehicle (BEV)**. For drivers of a BEV a well-developed charging infrastructure is therefore of enormous importance in order to prevent a stop due to an empty battery.
- **Plug-in Hybrid Electric Vehicle (PHEV)** are vehicles that can be refueled in two ways. In addition to the electric engine, a conventional combustion engine is also installed in the vehicle. If the SoC of the battery is exceeds a certain limit, the electric motor is used for locomotion. If the battery is empty, the second drive can be used. Due to the comparatively long charging times of batteries, the PHEV can be particularly advantageous for long journeys. However, to have a high benefit of the electric engine, a well-developed charging infrastructure is of great importance.
- The third variant of electric vehicles represent **Hybrid Electric Vehicle (HEV)**. In contrast to BEV and PHEV they cannot be charged via an external power source but are powered by excess energy (e.g. braking energy) while driving. Since the focus of this work is on the wired charging of electric cars, the HEV is not considered in detail. In the following the terms Electric Vehicle (EV) will therefore be used as synonyms for BEV and PHEV.

### 2.4.1. Mobility in Germany

Before going into more detail on consumption data and the distribution of EVs in the following sections, a brief overview of the general traffic behavior of Germans will first be given. The average distances traveled are a valuable reference for making statements about the amount of energy that must be provided. In the event that a given charging system is not able to cover the average energy demand, it will be

difficult to convince a potential customer to make an investment.
According to a study by the Federal Ministry of Transport and Digital Infrastructure based on data from 2017 [9], the average distance traveled by all inhabitants is around 39 km/day, see Table 2.4. Approximately 55 percent of this distance is traveled as a driver of a vehicle, which corresponds to about 21 km. Of course, this is only an average value and allows only limited conclusions to be drawn. When comparing a metropolitan region with a small town or village, clear regional differences can already be seen. If on average only 14 km/day are driven in the metropolis, it is 26 km/day in the small town [9]. It should also be taken into account that children and young people under 17 years of age cannot drive kilometers and therefore reduce the average. The analysis of the modal split of traffic volume by age group [9] also shows a continuous decline in the daily use of cars from the age of 60.

**Table 2.4:** Daily locomotion in Germany in 2017 [9]

| | Total population (82 million) | Ø Person |
|---|---|---|
| Total daily locomotion [km] | 3,214.00 million | 39.19 |
| As a driver of a vehicle (total) [km] | 1,754.00 million | 21.39 |
| As a driver of a (gas, diesel) car [km] | 1,607.00 million | 19.60 |
| As a driver of a truck [km] | 96.42 million | 1.18 |
| As a driver of a Motorbike, EV and others [km] | 50.58 million | 0.61 |

Due to the fact that several people can share a car, the distance per vehicle might be an even more interesting point. According to [9] the average mileage is 14.700 km/year which corresponds to a daily average of about 40 km/day. Further it is indicated that on average only two percent of the trips are over 100 km. In Finland, for example, the average driving distance of a car is a bit higher at around 50 km/day [33]. It should therefore be noted that the average values provide a valuable indication, but that a more detailed analysis is needed for the individual case.

### 2.4.2. Current Models

More and more manufacturers are now offering electrically powered vehicles in addition to conventional vehicles. Although the share of EV in the total vehicle market in Germany is still relatively low at under 1 percent (compare Table 2.6), German manufacturers also see great potential in electric-mobility. As early as 2017, the former CEO of Daimler AG announced that the company wanted to include at least ten different electrically powered vehicles in its product portfolio by 2022 [34].
Table 2.5 is intended to give a brief overview of current EV models. It should be noted that far more than the five models presented are available on the market. Nevertheless, it can be seen that the models differ greatly in their battery capacity and the associated range.
Based on the maximum range and the charging time specified by the manufacturers, the average charging range per hour is calculated in Table 2.5. The assumed charging power is 2.3 kW. Simplified, a linear charge is assumed, so that if a battery needs six hours to charge by 80 percent, then it will need one hour to charge by around 13 percent. For the range, this means that 13 percent of the maximum range can be charged within one hour. Of course this calculation represents only a rough orientation. The range also depends on many factors such as driving behavior, loading and other external factors. E.g. if a vehicle is in stop and go traffic and also has the air conditioning turned on, the range will be reduced compared to a continuous drive on a highway.
However, when comparing the charging distance per hour with the average distances traveled (see Section 2.4.1), a clear trend can be seen. Under normal, average circumstances, the battery could be fully charged after 3-4 hours at an average power of 2.3 kW. Under the assumption that a car is usually parked for way more than 4 hours overnight, it becomes clear that not every charging point has to provide high power charging.
In case of the manufacturer's specifications, it must also be observed whether consumption values are stated according to the New European Driving Cycle (NEDC) or Worldwide Harmonized Light Vehicles Test Procedure (WLTP) procedure. The values of the WLTP procedure are often higher than those of the NEDC procedure. However, since the WLTP procedure represents a more realistic consumption, according to EU Commission Regulation 2017/1151 the specification has been mandatory since June 1$^{st}$, 2017. The ranges given in Table 2.5 are therefore based

on WLTP values.

**Table 2.5:** Technical data of several current electric vehicles

| | Smart forfour EQ | VW e-Golf | Hyundai Kona Elektro | Opel Ampera-E | Tesla Model S |
|---|---|---|---|---|---|
| **Battery capacity** | 17.6 kWh | 35.8 kWh | 39.2 kWh | 60.0 kWh | 100.0 kWh |
| **Power** | 60.0 kW | 100.0 kW | 100.0 kW | 150.0 kW | 311.0 kW |
| **Driving range** | 128.0 km | 231.0 km | 289.0 km | 423.0 km | 510.0 km |
| **Charging time** | 80.0 %<br>6.0 h<br>2.3 kW | 100.0 %<br>17.0 h<br>2.3 kW | 100.0 %<br>19.0 h<br>2.3 kW | 6.0 km<br>0.5 h<br>2.3 kW | 11.0 km<br>1.0 h<br>2.3 kW |
| **Ø Charging distance/ hour** | 17.1 km | 13.6 km | 15.2 km | 12.0 km | 10.0 km |
| **Source** | [35] | [36] | [37] | [38] [39] | [40] |

### 2.4.3. Electric Vehicles in Germany

In August 2009, the German government published a national development plan on electric mobility [41]. The plan provides that by 2020 at least one million electric vehicles (BEV and PHEV) should be registered in Germany. However, the yearly published numbers from the Federal Motor Transport Authority (see Table 2.6) show that the target will probably not be reached. Although an annual increase of BEV and PHEV can be observed, with about 150,000 vehicles 85 percent are still missing to reach the target.
In its progress report [20], the National Platform for Electric Mobility, which was an advisory body of the Federal Government, therefore already stated in 2018 that the target of 1 million vehicles by 2020 not appear realistic until 2022.

As Table 2.6 shows, the proportion of all registered electric vehicles (BEV + PHEV) in Germany at the beginning of 2019 reached a level of around 0.3 percent. Based on the new registrations in 2018, a quota of about one percent can be determined according to the Federal Motor Transport Authority [46]. Compared with pioneering

**Table 2.6:** Development of EV in Germany compared to the total number of vehicles [42][43][44][45]

| | BEV | PHEV | HEV | Total vehicles |
|---|---|---|---|---|
| 01.01.2016 | 25,502 | N.A. | 130,365 | 45,071,209 |
| 01.01.2017 | 34,022 | 20,975 | 144,430 | 45,803,560 |
| 01.01.2018 | 53,861 | 44,419 | 192,291 | 46,474,594 |
| 01.01.2019 | 83,175 | 66,997 | 274,414 | 47,095,784 |

countries in the field of electro-mobility such as Norway, however, these values are quite low. According to the Norwegian Road Information Council (OLV), in the first half of 2019 a new registration rate of around 45 per cent could be determined in Norway [47].

# 3. Low Power Charging

In the previous chapter, the slow roll-out of EVs was discussed in more detail. In this context the so-called chicken and egg problem is often mentioned. Without an adequate infrastructure customers are rather hesitant when it comes to buying electric vehicles. On the other hand, investors are also unwilling to invest in new facilities if the demand is relatively low. In this context, low power charging is an approach to accelerate the expansion of the charging infrastructure.
In the following, the advantages and disadvantages of low power charging are compared. Furthermore, existing implementation strategies are described in more detail.

## 3.1. Advantages and Disadvantages of Low Power Charging

It can be seen that charging a battery with low power increases the charging time compared to charging it with high power [48]. If fast charging is required, such as at a highway service station, the low power charging approach is therefore not a suitable solution. When comparing the range of a fully charged battery (see Table 2.5) with the average driving distance of 40 km/day (see Section 2.4.1), it quickly becomes apparent that the battery normally provides enough energy for the entire day. In the event that charging points are available at home as well as at work, fast charging is therefore often not mandatory. Nevertheless, the question arises why fast charging of the battery should be avoided if the technical possibilities are available. On one hand, the battery lifetime can be reduced by charging with high power [48]. On the other hand, the costs of installing a fast charging point should be mentioned in this context. In order to transport high power, the cables must be adapted accordingly. In addition, a connection to the low-voltage grid may no longer be sufficient, so that a connection to a higher grid level or a larger transformer may be necessary [49]. In this context, the network load can also be mentioned. Due to the fact that a great amount of power is taken from the grid within a short period of time, the effort required to guarantee grid stability and avoid bottlenecks increases [50]. Approaches that try to reduce peak loads with the help of additional energy storage devices are already available [51], but the integration of such a system nevertheless continues to increase costs. According to a study by the Rocky Mountain Institute, the cost of a DC fast charging point can rise to over 70,000 EUR (over 80,000 US Dollars) (see Appendix A.3).

When charging with lower power, the loads on the energy grid are also much lower. Even though the same amount of energy is consumed over a longer period of time, the peak load is at a lower level. If the maximum power of a charging point is reduced to the point where it can be easily integrated into the existing network, the installation costs are also significantly lower. The use of the existing electrical infrastructure, such as the connection of street lights, could further reduce costs and accelerate the expansion of charging points. The spread of low power charging points is already more advanced in other countries than in Germany. Using the Finnish market as an example, a possible implementation is shown in the following section.

## 3.2. Solutions on the Finnish Market

The geographical location of Finland means that it is exposed to different climatic conditions than Germany. As a result, the general infrastructure also has different characteristics. Since the winters are often very cold and long, many parking lots are equipped with a power connection that can be used for auxiliary heating.


(a) Heating poles (b) Charging unit

**Figure 3.1:** Example of a heating pole charging solution (a)[Parking Energy] (b)[IGL]

Some Finnish companies take advantage of this special characteristic of the existing infrastructure and additionally install charging units for electric vehicles on top of the heating poles. The left picture in Figure 3.1 shows a parking lot equipped with the aforementioned heating poles. The right picture shows the charging unit which can replaces the grey boxes of the heating poles. The maximum output is usually limited to a few kilowatts.

For the private sector, too, there are various solutions available in the area of low power charging. The installation of the charging unit is based on the principle of providing charging stations as cost-effectively as possible by using existing connection capacities. With the help of an appropriate billing system, property owners can make the electricity available to other users at their sites as well. Using an app-based system, a driver can quickly locate a charging station close to his/her current location. An example of a charging system from the company Cation OY is shown in Figure 3.2.


(a) Charging unit (b) App based charging

**Figure 3.2:** Example of charging solutions at residential buildings [Cation OY]

The technology of low power charging is also used in larger car parks. The company Parking Energy, for example, advertises that equipping of around 250 parking spaces with an adequate low-power charging infrastructure can be realized for about 90,000 EUR. For less than 400 EUR, it is therefore possible to equip a single parking lot with the appropriate cabling. The charging unit itself is finally made available to the customer via a monthly usage fee, which is either paid by the landlord or by the driver. The invoicing of the amount of energy purchased as well as the administration of the charging points will also be carried out by the aforementioned company. The image on the left in Figure 3.3 shows so-called EV ready parking spaces. Each parking space is equipped with an appropriate infrastructure. If a customer buys an EV, the parking lot can be quickly retrofitted with a charging unit. As shown in Figure 3.3, this can be done quickly by attaching the charging unit to the connector unit.


(a) EV ready parking facility

(b) Charging unit

**Figure 3.3:** Example of EV ready parking facility [Parking Energy]

# 4. Low Power Charging at Residential Buildings

The goal of the analysis is to use the existing infrastructure of residential buildings as efficiently as possible to install charging points without facing major installation costs. In the following two tools will be developed to help investors and real estate owners to evaluate investment opportunities.

A key element for the decision for or against an investment is the given framework. On the one hand, the building connection provided by the grid operator represents the upper limit of how much power can be taken from the energy grid. On the other hand, the load profile of the building is the second essential criterion for determining how many free capacities the building connection has. These values can be calculated with a suitable smart meter and can be determined relatively easily by taking a look into the building plan of the real estate. However, according to Cation Oy (K. Koponen, personal communication, 2019), a Finnish provider of low power charging infrastructure, many customers are overwhelmed by these values and can therefore hardly draw any conclusions from them. In order to reduce the resulting uncertainties, one aim of this thesis is to make the data on peak load and building connection fuses more tangible for the end customer.

## 4.1. Make Charging Tangible for the End Customer

In a first step, a simple Java tool is going to be developed which converts the available power as a function of time into a range value in kilometers. Every car owner can easily check their daily or weekly driving range by resetting the trip. A kilometer value therefore seems way more valuable than data e.g. related to the building connection fuse.

### 4.1.1. Available Capacity

The basis for the range calculating value is the available capacity of the building infrastructure. For its calculation it is assumed that the charging infrastructure cannot adapt to the current power consumption of the house. In order to ensure that the maximum permissible current is not exceeded and that the fuse is not triggered, the maximum load of the house is taken as a reference. As Figure 4.1 shows, it can be assumed for the model that the maximum capacity ($P_{max}$) minus the peak load ($P_{peak}$) is available to the charging infrastructure at all times ($P_{available}$).

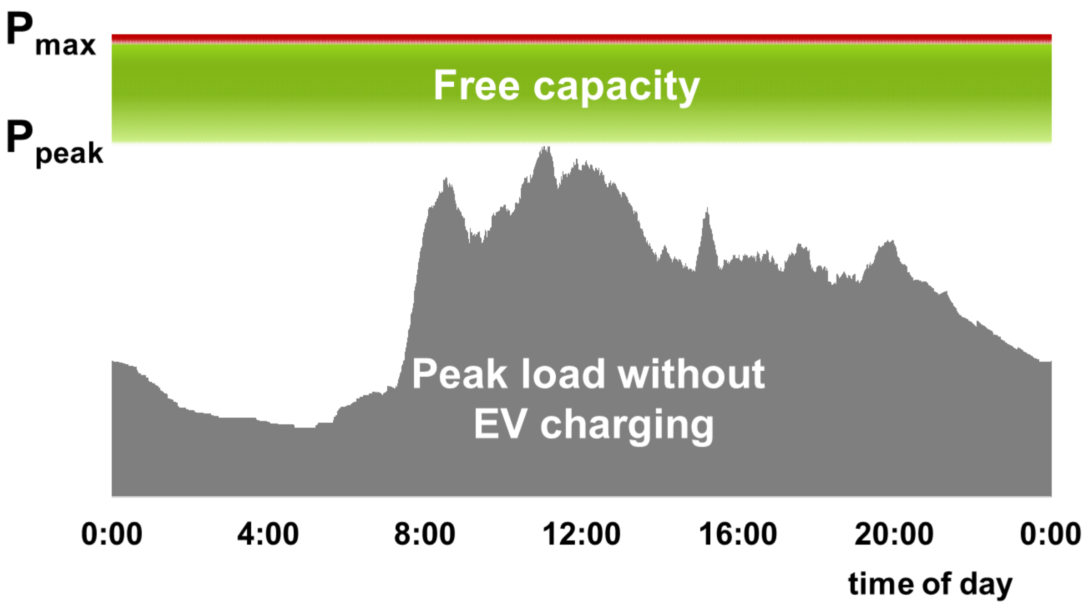



**Figure 4.1:** Example illustration of free network capacities

The maximum available capacity can be derived from the building connection fuse ($I_{max}$). With a 3-phase building connection and a grid voltage of 230 Volt the maximum and the maximum available capacity are defined as follows:

$$P_{max}\ [W] = I_{max}\ [A] * 3 * 230\ [V]$$

$$P_{available} = P_{max} - P_{peak}$$

Other parameters required to determine the rechargeable range are the consumption values of the electric vehicles and the charging losses of the onboard chargers. In the following, these parameters are explained in more detail and are going to be defined accordingly.

### 4.1.2. Energy Consumption

The average energy consumption is derived from data provided by the German Federal Motor Transport Authority, which determines the fuel consumption of many vehicles. The data for some selected vehicles can be found in Table 4.1. If the average of these vehicles is calculated, an mean consumption of 17 kWh/100km ($Con_{high,NEDC}$) can be determined. If, however, sports cars, SUVs and big vans are excluded from the analysis, the average consumption drops to 14.7 kWh/100km ($Con_{med,NEDC}$).

**Table 4.1:** Energy consumption of EVs regarding the German Federal Motor Transport Authority [52]

| Manufacturer | Model | Consumption [kWh/100 km] |
|---|---|---|
| BMW | i3 | 13.6 |
| CITROEN | C-Zero | 12.6 |
| Daimler | EQ forfour | 13.0 |
| FORD | Focus Electric | 15.4 |
| KIA MOTOR | SOUL | 14.7 |
| NISSAN | NISSAN LEAF | 15.0 |
| Opel | Ampera-e | 15.6 |
| RENAULT | ZOE | 14.6 |
| TESLA | Model S | 18.7 |
| Volkswagen | Golf | 13.9 |
| Volkswagen | UP! | 11.7 |
| VOLVO | C30 | 17.5 |
| **Average:** | | **14.7** |
| | | |
| Daimler | Vito E-Cell | 25.2 |
| Audi | R8 e-tron | 21.4 |
| TESLA | Model X | 22.6 |
| Mercedes-AMG | SLS AMG E-Drive | 26.8 |
| **Average:** | | **17.0** |

Comparing the consumption data of the Federal Motor Transport Authority with the consumption data of the manufacturers (see Table 4.2), it can be observed that the consumption values come close to the values determined by NEDC test procedures. Since the NEDC test procedure determines consumption under optimized conditions, the consumption values must be corrected for the design of the model described above.

**Table 4.2:** Energy consumption of EVs regarding the manufacturer specifications

| Manufacturer | Model | Power [kW] | Consumption [kWh/100 km] | Source |
|---|---|---|---|---|
| Volkswagen | Golf | 100 | 13.2 (NEDC) | [53] |
| BMW | i3 | 75 | 13.1 (NEDC) | [54] |
| NISSAN | NISSAN LEAF | 110 | 18.5 (WLTP) | [55] |

Assuming that higher $CO_2$ emissions are in line with higher energy consumption, the energy consumption is according to [56], [57] already about 22-25 percent higher with the more realistic WLTP test procedure. If, for example, the consumption values of the Nissan Leaf are compared, it can be seen that the test procedures determined according to WLTP are around 23 percent higher than those of the Federal Motor Transport Authority. It should be noted that the performance of the engines used differs, which can also have an effect on higher energy consumption. However, there is still a trend towards higher energy consumption. In [56], [57] it is further stated that also the WLTP values would not yet correspond to the real consumption. In comparison to the NEDC values the real consumption is about 30-33 percent higher. The "Ecotest" conducted by the ADAC in 2018 comes to the similar result and shows an increase in consumption of over 30 percent (Appendix A.2). It should be noted that the ADAC test already includes charging losses, so the actual consumption is lower. For the design of the model, the worst case is assumed at this point, so that the consumption values of the Federal Motor Transport Authority are increased by 33 percent.

$$Con_{med,real} = Con_{med,NEDC} * 1.33 = 19.6kWh/100km$$

$$Con_{high,real} = Con_{high,NEDC} * 1.33 = 22.6kWh/100km$$

### 4.1.3. Power Loss

The power losses that occur when charging the EV cannot be neglected when designing the model. An ADAC study has shown that only between 82.8 and 95.2 percent of the current drawn from the grid reaches the car's battery. On average, this results in an efficiency ($\eta$) of 88.5 percent (see Annex A.1).

### 4.1.4. Range Calculation

All essential factors are finally determined for the determination of the potential which can be charged in a certain period of time. The above determined available power ($P_{available}$) multiplied by the efficiency ($\eta$) and the charging time ($t$) results in the energy available for the battery ($E_{battery}$).

$$E_{battery} = P_{available} * \eta * t$$

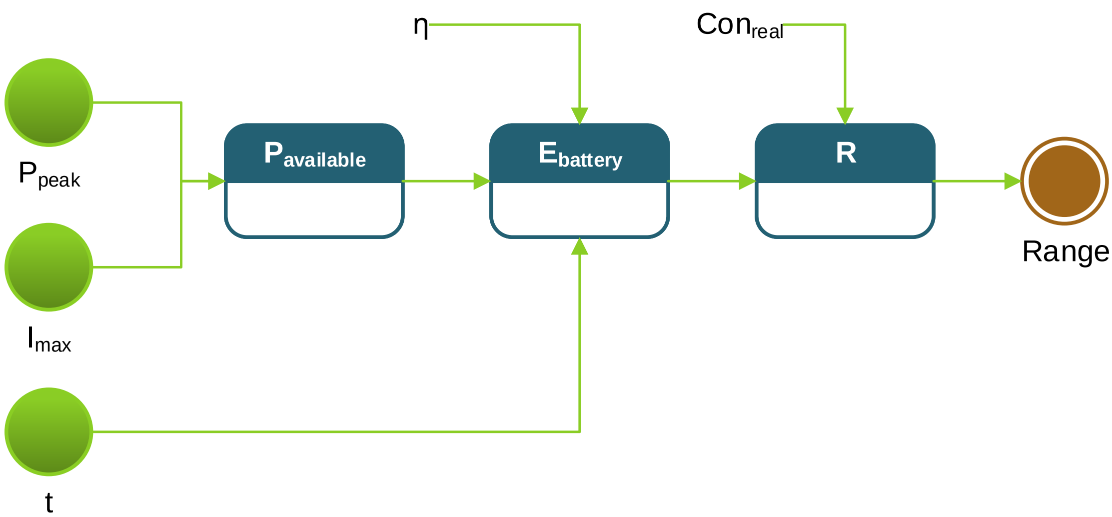
If a normal consumption of the EV ($Con_{med,real}$) is assumed, the range ($R_{med}$) can be determined as follows:

$$R_{med} = E_{battery}/Con_{med,real}$$

All necessary parameters are therefore determined in order to derive the range potential from the free line capacity. In the following sections the implementation of the Java tool will be briefly discussed. Subsequently, the actual analysis is described in more detail.

### 4.1.5. Java Implementation

Figure 4.2 shows the basic structure of the simple Java tool graphically. The peak load of the building, the fuse size and the charging time are representing the input parameters. By taking average values for charging losses and consumption data, the theoretically achievable range is subsequently determined. It should be noted that in reality these cannot be achieved by all vehicles or only by several vehicles charged in parallel due to battery limits and maximum charging performance.




| | | | | | |
|---|---|---|---|---|---|
| $P_{peak}$ | = | Building peak load | η | = | Efficiency |
| $I_{max}$ | = | Building connection fuse | $E_{battery}$ | = | Charged energy |
| t | = | Charging time | $Con_{real}$ | = | Real consumption |
| $P_{available}$ | = | Available capacity | R | = | Range |

**Figure 4.2:** Simplified illustration of range calculation process

### 4.1.6. Analysis

As described above, certain input parameters are required for the application and evaluation of the tool. For data protection reasons, however, it is almost impossible to use a qualitative source at this point. Since sizes for fuses and consumption can vary greatly, it would not be even possible to make a generally valid statement with suitable data. In order to be able to give a rough orientation, the following refers to the German standard DIN-18015-1, which defines planning principles for electrical systems in residential buildings. It is assumed that with an increasing number of apartments connected to a building connection fuse, the probability of peak loads occurring at the same time decreases. Consequently, if the number of apartments increases, the peak load will increase to a lower extent. In the further progress of the work, the simultaneity factor $(s)$ is used in this context, which represents peak load

growth as a function of the number of apartments [58]. The expected peak loads of the buildings are shown in a diagram in the standard which can be found in Annex A.2.
Regarding to standard DIN-18015-1 additional reserves must be provided for future system modifications and extensions. The minimum reserve should be at least 20 percent of the total capacity. For further analysis, it is therefore assumed that an additional 20 percent of the expected peak load may be available to a potential charging system. In this context, Table 4.3 below shows examples of some possible size combination. In general, however, the values should be considered with caution, as the actual peak loads as well as the free capacities may vary.

**Table 4.3:** Expected peak loads regarding to standard DIN-18015-1

| Apartments | 1 | 5 | 10 | 20 | 35 | 50 | 75 | 100 |
|---|---|---|---|---|---|---|---|---|
| **Expected peak load of the building [kW]** | 14.5 | 41.0 | 55.0 | 72.0 | 85.0 | 95.0 | 103.0 | 105.0 |
| **Additional capacity for future installations [kW]** | 2.9 | 8.2 | 11.0 | 14.4 | 17.0 | 19.0 | 20.6 | 21.0 |
| **Resulting building connection capacity [kW]** | 17.4 | 49.2 | 66.0 | 86.4 | 102.0 | 114.0 | 123.6 | 126.0 |

Especially with a small number of apartments, the tool can provide a valuable overview of the potential of the charging infrastructure. However, as the number of apartments grows, the probability increases that residents using the charging system at different times of the day. If the charging processes are evenly distributed throughout the day, a considerably higher capacity can be taken from the system. If, on the other hand, all or at least most of the vehicles charge at the same time, the available energy is reduced. In the next section, a further development of the tool is therefore presented, which should better illustrate the individual behavior of the users.

## 4.2. Simulation of Different Charging Events

The simple range calculation tool described above enables property owners to gain a relatively quick overview of the available potential for charging EVs. In order to ensure that the system is not only designed for the average case, but also offers a satisfying service for exceptions such as longer distances and shorter charging times, a more detailed analysis of is necessary. The following therefore describes the further development of the above model, which is intended to represent the Quality of Service (QoS) under various combination. It is assumed that in the afternoon / evening residents want to connect their car to the charging station. The next morning they are intend to leave the parking lot with a fully charged battery.

### 4.2.1. Input Parameter

In addition to the information about the peak load ($P_{peak}$) of the building and the building connection fuse, the number of charging points to be set up in particular plays an important role. Due to the fact that the charged energy depends on the charging time, the average arrival and departure times are equally important. Since it is to be assumed that there will be a certain variance in arrival or departure times, it is also reasonable to enter a variance interval. As already mentioned in Section 2.4.1, the average daily driving distance of a car in Germany is about 40 km. Of course, this value depends on many factors and should therefore also be requested for each individual case. Similar to the charging time, daily fluctuations are to be expected for the distance traveled, so that a scattering interval must also be queried in addition to the average value. The maximum charging power of the system is the last important parameter for the design of the tool. This is to prevent the charging power of a car from reaching undesired levels in the simulation. All necessary parameters are summarized in Table 4.4.

**Table 4.4:** Input parameters for simulating different charging processes

| **Input parameters** | |
|---|---|
| $P_{peak}$ | Peak load w/o EV |
| $I_{max}$ | Building connection fuse |
| $NoC$ | Number of charging stations/ cars |
| $P_{char,max}$ | Maximum charging power |
| $t_{arr}$ | Average time of arrival |
| $arr_{int}$ | Arrival variation interval |
| $t_{dep}$ | Average time of departure |
| $dep_{int}$ | Departure variation interval |
| $D_{day}$ | Average daily driving distance |
| $D_{int}$ | Driving distance variation interval |

### 4.2.2. Functionality of the Model

Taking into account the input parameters mentioned above, the following section describes the functionality of the model in more detail. The main goal is to cover a wide spectrum of different charging scenarios to make a fundamental statement about the QoS.
In order to implement the model, it is therefore necessary to assign each vehicle an individual parking time series as well as an individual amount of required energy. For this purpose, a random generator ($R$) is used which randomly determines time and distance values out of the specified intervals (see Table 4.5). With the help of the average consumption (see Section 4.1.2) and the individual driving distance, it is possible to determine the required amount of energy for each car.

**Table 4.5:** Car parameters for simulating different charging processes

| **Car**$_i$ | | | |
|---|---|---|---|
| Random value | $R$ | = | [0;1] |
| Arrival time | $t_{arr,i}$ | = | $t_{arr} + (R_{i,1} - 0.5) * arr_{int}$ |
| Departure time | $t_{dep,i}$ | = | $t_{dep} + (R_{i,2} - 0.5) * dep_{int}$ |
| Driving distance | $D_{day,i}$ | = | $D_{day} + (R_{i,3} - 0.5) * D_{int}$ |
| Required energy | $E_{req,i}$ | = | $D_{day,i} * Con_{med,real}$ |

The calculation of the available capacity ($P_{available}$) of the charging system is once again determined using the peak load of the building and the building connection fuse (see Section 4.1.1). The simulation is based on the assumption that the available power is distributed equally among those cars to be charged that are present ($NoCc_J$). If the available power per car ($P_{av,car,j}$) is higher than the maximum allowable power ($P_{char,max}$), the charging power is limited accordingly. Due to the fact that only low power charging is considered, it can be assumed that the charging performance does not decrease significantly with an increasing SoC. Although the effect also occurs in this case, the resulting error is relatively small according to [27]. In the model, the available power is recalculated every minute. If another car is connected or if the battery is fully charged, the power will be redistributed. The calculation of the missing required amount of energy ($E_{req,J}$) must therefore also be carried out in minute cycles. It should be kept in mind that charging losses have to be taken into account again when determining the amount of energy charged. As with the range calculation tool, these are included in the calculation via the efficiency $\eta$.

**Table 4.6:** Time depending parameters for simulating different charging processes

| **Minute**$_j$ | | | |
|---|---|---|---|
| Number of cars charging | $NoCc_j$ | | |
| Available power per car | $P_{av,car,j}$ | $=$ | $P_{available}/NoCc_j$ |
| | $P_{av,car,j}$ | $\leq$ | $P_{char,max}$ |
| Charged energy | $E_{cha,J}$ | $=$ | $\sum_{j=0}^{J} P_{av,car,j} * 1/60 * \eta$ |
| Remaining missing energy | $E_{req,J}$ | $=$ | $E_{req,0} - E_{cha,J}$ |

For the evaluation of the model, it is assumed that the customer expects that the car can be fully charged for the duration of the parking time. If so, the QoS is rated as 1. In the event that the vehicle could only be partially charged, simplifying a QoS of 0 is assumed. The results are strongly dependent on the values of the random generator. In order to improve the significance, a correspondingly large sample must be selected. In the following, this is equated with the number of days in a year. For each day, new random values are created for each vehicle. This way it is tried to map the best case scenarios as well as the worst case scenarios accordingly and to include them in the evaluation.

### 4.2.3. Output Parameter

For the final output, the number of all successfully completed charging processes is set in relation to the total number of all charging processes ($QoS$). A value of 100 percent therefore represents a completely satisfying scenario.

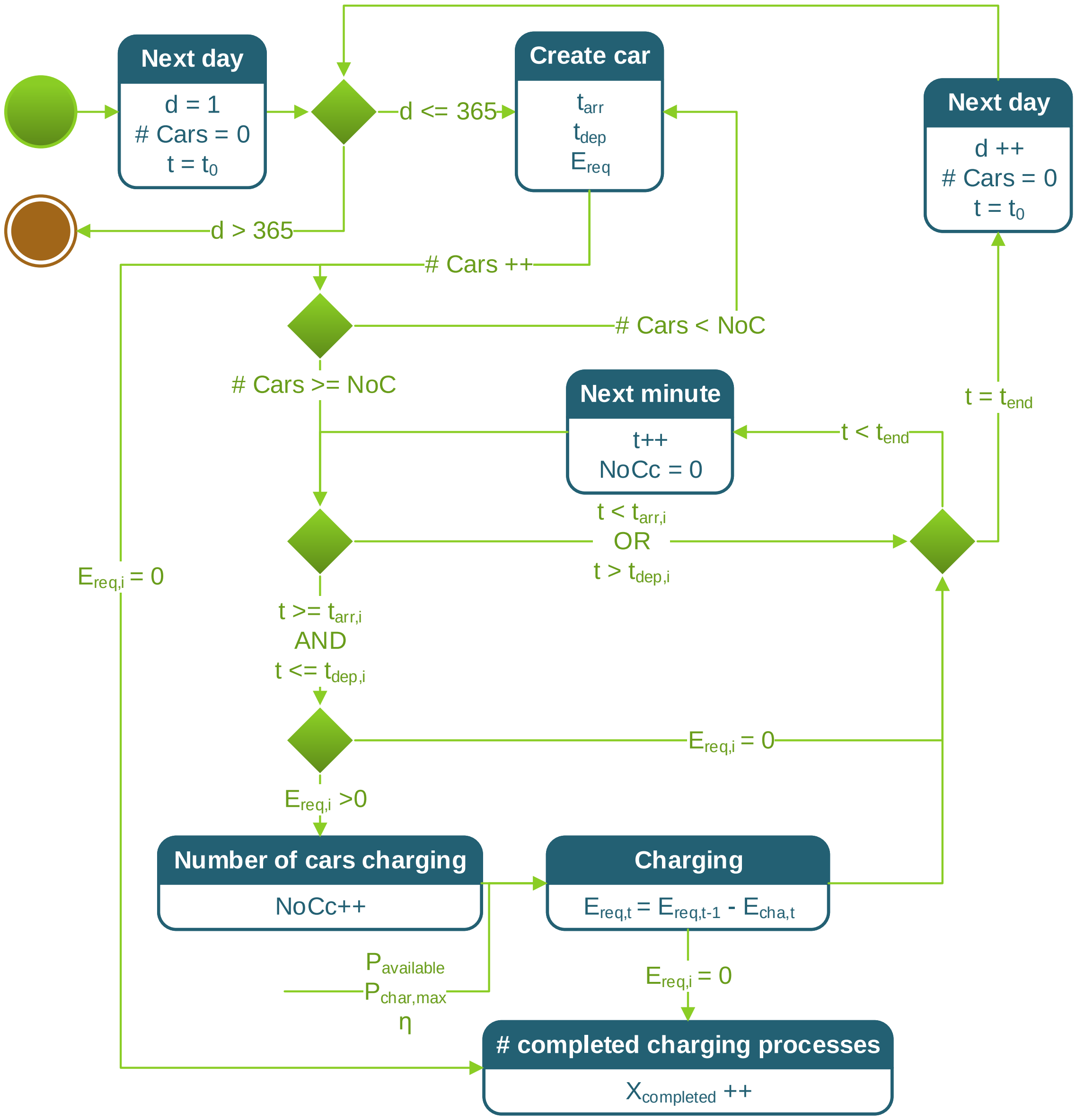
**Table 4.7:** Output parameters/ results of simulating different charging processes

| **Output parameters** | | | |
|---|---|---|---|
| # simulated charging processes | $X_{total}$ | $=$ | $NoC * NoD$ |
| # completed charging processes | $X_{completed}$ | $=$ | $\sum_{k=0}^{NoD} \sum_{i=0}^{NoC} (E_{req,t_{dep,i}} = 0)$ |
| Quality of Service | $QoS$ | $=$ | $X_{completed}/X_{total} * 100\%$ |

### 4.2.4. Java Implementation

For the implementation of the tool in Java, further boundary and start conditions have to be defined in addition to the aforementioned input parameters and calculation rules. For this purpose, a start time ($t_0$) and end time ($t_{end}$) must first be defined. Due to the fact that main charging cycles are assumed to occur during the night, 12 o'clock at noon is selected. When designing the arrival and departure intervals, these have to be limited in such a way that $t_0$ and $t_{end}$ cannot be exceeded. A special aspect must also be noted when implementing the individual driving distance. If the scattering interval is twice as large as the value of the mean distance traveled, negative distances are theoretically possible as well. To prevent this, negative values must be set to zero. In order to keep the mean distance traveled equal to the specified mean value, the amount of a negative distance traveled must be transferred to the next simulated vehicle. For this vehicle, the distance traveled is now reduced accordingly. If the distance traveled for this vehicle is going to end up negative as well, it is again passed on to the next vehicle.

Figure 4.3 shows the main processes of the simulation. After generating individual vehicle data, the system checks every minute whether a vehicle is participating in the charging process or not. After one day ($t_{end}$) all vehicle data are deleted and the simulation starts again for the next day. After 365 runs the simulation reaches its end. The number of fully charged EVs is stored in a variable ($X_{completed}$). If a vehicle is not moved on a specific day and therefore does not participate in the charging process, it will still be evaluated as successfully charged.




| | | | | | |
|---|---|---|---|---|---|
| $t_{arr}$ | = | Time of arrival | $t_{dep}$ | = | Time of departure |
| $t_0$ | = | Start time of simulation | $t_{end}$ | = | End time of simulation |
| $P_{available}$ | = | Available capacity | $P_{char,max}$ | = | Maximum charging power |
| $\eta$ | = | Efficiency factor | $E_{req}$ | = | Required energy |
| $E_{cha}$ | = | Charged Energy | NoC | = | Number of charging stations |
| NoCc | = | Number of cars charging | $X_{completed}$ | = | # completed charging processes |
| d | = | Simulation days | | | |

**Figure 4.3:** Simplified illustration of charging simulation process

### 4.2.5. Analysis

The presented tool offers the possibility to change the charging process by different parameters. For an analysis it is therefore necessary to define an initial scenario, which forms the basis of the analysis. Based on the results, individual parameters can be varied to evaluate their influence on the system.
For the initial scenario, the peak load specified in the DIN-18015-1 standard is used once again. As in Chapter 4.1.6, it can be assumed that 20 percent additional free line capacities are available for new installations. For the daily distance traveled, the average value of about 40 km/day per car is used (cf. Section 2.4.1). In the model, 40 km/day represent the average value too, while the actual distances traveled vary between 0 and 80 km/day. The average parking time is assumed to be 10 hours. Arrival and departure times can vary by up to two hours. For the actual parking time, this gives an interval of 8 - 12 hours. The last parameter to be defined is consumption. For the initial scenario, the previously determined average consumption of 19.6 kWh/100km (cf. Chapter 4.1.2) is assumed.
Nevertheless, the penetration rate of EVs has the greatest influence on the results. Whereas the penetration rate at the beginning of 2019 was far below one percent (see Table 2.6), a penetration rate of about 100 percent is conceivable in the long term. In the results chapter the initial scenario is therefore presented for different penetration rates. In a second step of the analysis, a separate variation of individual parameters takes place. On the one hand, it is analyzed how the change in free capacities affects the result. On the other hand, the influence of a shorter parking time is of interest. In addition, a variation of the distances, as well as a change of the arrival and departure interval will be considered in more detail.
Due to the simultaneity factor assumed in DIN-18015-1, the capacity of the building connection increases much slower with an increasing number of apartments. Consequently, the results are also strongly dependent on the number of apartments considered, so that the analysis is always carried out for different numbers of apartments.

# 5. Analysis and Optimization of Real Parking and Charging Data

In this chapter the analysis of historical low power charging data is described. The basic charging behavior of Electric Vehicle (EV) drivers thereby represents a central element. By comparing the deviation between charging and parking time the flexibility potential of each charging processes will be determined. Based on the results, two optimization methods are presented in a further step, which shall reduce the peak load by load shifting mechanisms. If a general reduction of the peak load should appear to be possible, the installation of further charging points can be considered without exceeding the limits of the building infrastructure.

The aim of the analysis is to show the potential of smart scheduling to reduce the peak load and therefore avoid bottlenecks in the system. Figure 5.1 shows the procedure graphically. For the example scenario only the charging process of car 2 is completely inflexible. Particularly with car 1 and car 4, however, there is a great potential for flexibility.

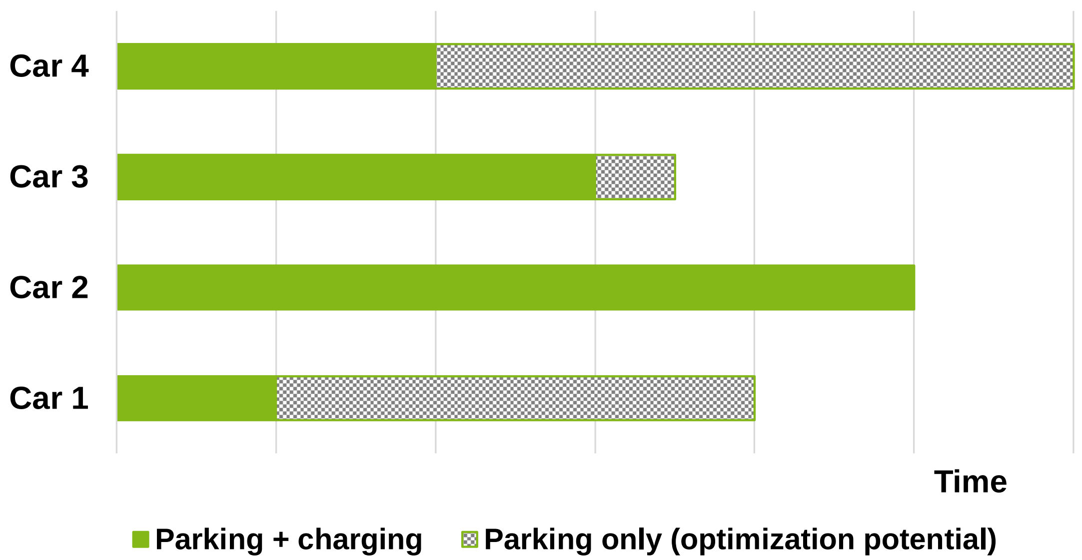



**Figure 5.1:** Illustration of the optimization potential of different charging processes

In order to use these flexibility, it is essential to know in advance how much energy is going to be charged in which time period. Within the scope of this work, it is assumed that this information will be received from the customer, for example via a suitable discount system. However, the concrete design of such a system will not be examined in detail at this point. Another important information for a real-time application is the prediction of when and how many vehicles can be expected. If, for example, many vehicles are expected to arrive at midday, it should be taken into account in the charging strategy for vehicles arriving in the morning. Due to the fact that the analysis of this work is based on historical data, it is not necessary to use a prediction algorithm at this point. For the implementation of load balancing in a real system, however, knowledge about the user behavior is elementary.

## 5.1. Data

The analysis is based on around 25,000 charging sessions that have been gathered at various locations in the Helsinki metropolitan area in Finland. While the first data set was recorded in September 2017, the last charging session took place in July 2019. Table 5.1 provides a first overview of the used data whereat the left column indicates the name of the respective parking facility. An explanation how the respective values were collected and calculated is given later in this chapter. A more detailed breakdown and analysis of the data takes place in Chapter 6 and Chapter 7. At this point, however, it should be pointed out that the table illustrates the great potential for an optimization. Despite relatively low charging power, the average parking time exceeds the average charging time to a large extent. A shift of individual charging processes can therefore lead to a reduction of the peak load.

It can be assumed that the charging behavior can vary significantly depending on the chosen location. If, for example, a charging point is installed directly in front of a residential building, it can be assumed that an EV has a longer parking time than at a charging point in front of a grocery store. For the analysis, the charging data are therefore divided into the following three categories.

**Category 1 - Public Parking Lots**: Public parking lots and garages that can be used by all electric cars, such as those at a shopping mall.
**Category 2 - Commercial Parking Lots**: Company parking lots where employees or visitors can park and charge their cars. Parking lots are normally not intended for

the public.

**Category 3 - Residential Parking Lots**: Residential parking lots at an apartment complex that can be used by the residents. In comparison with the two previous categories, charging can be expected at night times.

**Table 5.1:** Parking facility dependent charging characteristics

| | Number of sessions | Ø parking time | Ø charging time | Ø charged energy | Ø charging power | Ø charging current* |
|---|---|---|---|---|---|---|
| **C Parking** | **6,330** | 07:14 h | 04:20 h | 6.88 kWh | 1.92 kW | 9.25 A |
| **E Parking** | **2,692** | 05:31 h | 03:27 h | 5.89 kWh | 1.79 kW | 8.95 A |
| **H Parking** | **1,444** | 06:14 h | 03:42 h | 6.34 kWh | 1.83 kW | 8.91 A |
| **I Parking** | **1,442** | 06:34 h | 03:37 h | 5.45 kWh | 1.66 kW | 8.38 A |
| **K Parking** | **2,436** | 07:00 h | 04:30 h | 8.72 kWh | 2.02 kW | 9.05 A |
| **P Parking** | **449** | 11:13 h | 04:49 h | 5.22 kWh | 1.22 kW | 6.31 A |
| **R Parking** | **2,666** | 01:44 h | 01:22 h | 2.68 kWh | 2.09 kW | 9.98 A |
| **S Parking** | **1,029** | 05:52 h | 03:52 h | 5.71 kWh | 1.68 kW | 8.92 A |
| **X Parking** | **5,703** | 02:56 h | 01:25 h | 6.86 kWh | 4.54 kW | N.A. |
| **Others** | **614** | 07:52 h | 03:46 h | 5.66 kWh | 1.71 kW | 8.76 A |

*Average current during 90 percent of the charging time. Fluctuations at the beginning and end of the charging process are therefore excluded.

Table 5.2 provides a summary of how much data of the respective category will be used as a basis for the later analysis. The category of public parking spaces is by far the largest block at this point. In total, charging data are available from 12 different locations, of which 7 are public parking facilities.

**Table 5.2:** Charging Session Data

| | Public Parking Lots | Commercial Parking Lots | Residential Parking Lots |
|---|---|---|---|
| Locations | 7 | 4 | 1 |
| Outlets per Location | 8 - 80 | 10 - 36 | 6 |
| Charging Sessions | 20,382 | 4,664 | 449 |

From the data sets it is possible to read out the plug-in as well as the plug-out times. It is assumed that a customer does not remove the charging cable until driving away from the parking lot. The time between the aforementioned time stamps can therefore be assumed as the total parking time. Although it is possible that the real parking time exceeds the time between the plug-in and plug-out time stamps, it appears rather unlikely and is therefore not taken into account at this point. In order to determine the pure charging time, the current flow is analyzed more closely. If the battery of the vehicle is fully charged, a current flow of zero is to be assumed. This point in time can also be taken from the data set. The charging time is therefore defined by the time between the plug-in and the end of the current flow time stamp. The respective charging power is derived from the total amount of energy charged. Basically, it can be assumed that the maximum charging power decreases with an increasing level of charge. Due to the fact that low power charging does not charge with the maximum charging power of the battery, an approximately constant charging power can be assumed. According to [27], the resulting error is relatively small. To determine the charging power, the amount of energy charged is therefore divided by the charging duration. Information about the current SoC of the battery cannot be taken from the data set. However, if the parking time exceeds the charging time, it can be assumed that the battery is fully charged.

In order to reduce the complexity of the analysis, a compromise must be made regarding the choice of the analysis interval. As can be seen in the results chapter (see Chapter 6.2.1), the average parking time of all three parking categories is longer than five hours. With an interval size of 15 minutes, the expected deviation of the results from a smaller analysis interval is therefore quite small. For the further work, exactly this interval size will be used. Before the data analysis begins, the data set must be adjusted accordingly. The amount of energy charged is not changed and is assumed to be constant. Due to the fact that parking and charging times can change due to an analysis interval of 15 minutes, the charging capacity must be corrected accordingly. The calculation of the new parking and charging intervals ($time_{new,i}$) can be taken from Formula 5.1. If an interval ($time_{orig,i}$) is shorter than 15 minutes, it will be rounded up to full 15 minutes. For all other cases, the remainder of an integer division of 15 is considered more closely. If this value is less than 7.5 minutes, it is subtracted from the interval. Otherwise, the difference between 15 and the corresponding value is added to the interval.

$$time_{new,i} = \begin{cases} 15 & time_{orig,i} < 15 \\ time_{orig,i} - mod(time_{orig,i}) & mod(time_{orig,i}) < 7.5 \\ time_{orig,i} + 15 - mod(time_{orig,i}) & else \end{cases} \tag{5.1}$$

The modified charging power value ($power_{new}$) results according to Formula 5.2. The original charging power ($power_{orig}$) is determined with the quotient of the original and the modified charging duration.

$$power_{new} = power_{orig} * \frac{time_{orig,i}}{time_{new,i}} \tag{5.2}$$

The following section describes in more detail the analysis of the data, which is carried out separately for each of the mentioned categories. The first step provides a basic overview of the characteristics of the data series. The charging behavior of the EV owners, which is referred as the baseline scenario, will then be examined in more detail. Based on this, in a further step two optimization approaches will be presented, which are supposed to reduce the peak load by load shifting mechanisms.

## 5.2. General Data Analysis

Before analyzing the individual charging events, a general characteristic of the entire charging set is of interest. In a first step, the average parking and charging times are calculated. Based on their size, initial statements can already be made about the success of a possible smart scheduling algorithm. Another valuable statement can be derived from the percentage of flexible charging sessions out of the total number of sessions. For the analysis it is assumed that a charging process can be classified as flexible if the parking time is at least seven minutes longer than the charging time. The reason for this is the fact that the analysis is carried out every quarter of an hour, making it necessary to round up and round off the time series accordingly. Finally, the average amount of energy consumed is calculated. With an average consumption of 19.6 kWh/100km (see Chapter 4.1.2) and charging losses of 11.5 percent (see Chapter 4.1.3), the average distance traveled can be calculated. Comparing the results with the average distances traveled by all vehicles (including non-electric cars) makes it possible to determine the general validity of the analysis.

## 5.3. Load Profile - Real Charging Data

The objective of analyzing the original scenario is to obtain an overview of the load profile of the aggregated charging processes. In order to use the given infrastructure as efficiently as possible, peak loads are of particular importance.
For the characteristic of the load curve it is assumed that it has a daily recurring form. As a result, the analysis can be performed separately for each day. However, it can be seen that the shape of an individual load curve can vary. For example, it can be assumed that a different daily routine during the vacation period also leads to a different charging behavior. In order to be able to make a general statement, all load curves are summed up and an average profile is determined. In addition to the aggregation of the load curves, the peak loads of all days considered are added up. Peaks can occur at different times of the day and therefore differ in sum from the peak of the aggregated load curves. A later comparison of the value with that of the optimized load curves will show the optimization potential of the selected optimization approach.

The actual processing of the data takes place with the help of a Java-based tool. First all data of the respective location are read in via a SQLite database link. A timer is then used to check at intervals of 15 minutes which vehicles are present at a particular time. By adding the charging power of all vehicles which are present, the total load profile is determined and temporarily stored. In another loop, the individual load time series of each day are combined and added together. The results are then stored again in an SQLite database. To aggregate the peak loads of the individual days, the temporarily stored time series are read in again via Microsoft Excel and the individual peak values are added up.

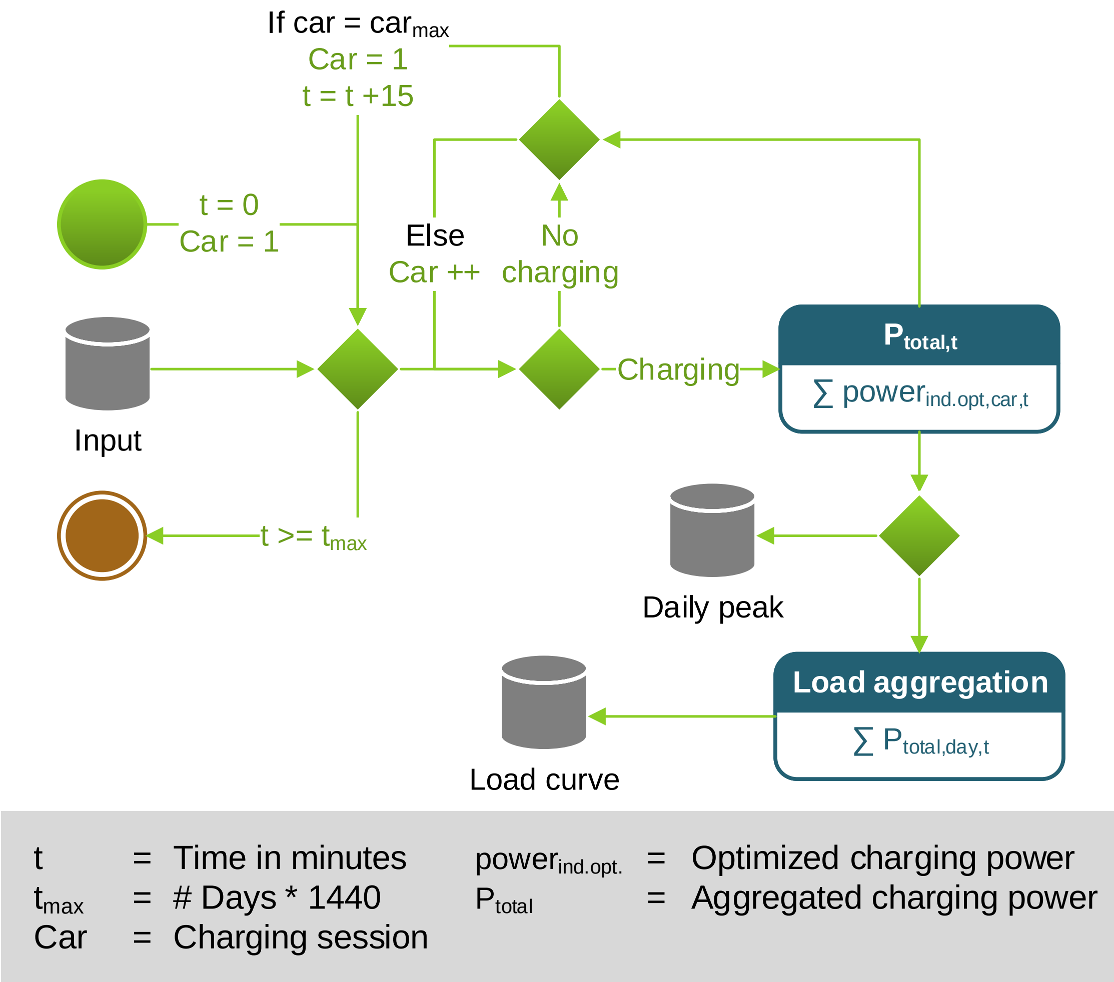



**Figure 5.2:** Simplified illustration of real data analysis

In the first step, all data of the respective category are considered and a total load curve is generated. For later comparison with the results of the optimized time series, the analysis is also carried out for individual locations.

The next chapter looks at a first simple optimization approach. By a corresponding load shift of individual vehicles the peak of the resulting total load shall be reduced.

## 5.4. Individual Optimization

The approach of the individual optimization is to minimize the peak load of each individual charging process in order to reduce the total load. If in the original scenario the charging time is equal to the parking time, the constant assumed power consumption is already the optimum. In contrast, the situation is different with flexible sessions. The peak load can be reduced by using the entire parking time as the charging time. The optimal case is a constant charging power over the entire parking time. The aggregation of parallel charging processes finally provides the optimized load curve.

In order to realize the optimization, modifications to the input data have to be made in the first step. It is determined that the data will be read in on a daily basis, so that the data set must be divided accordingly. By splitting the total time series into individual time series, it should be noted that individual charging processes can also be split into two sub-processes.

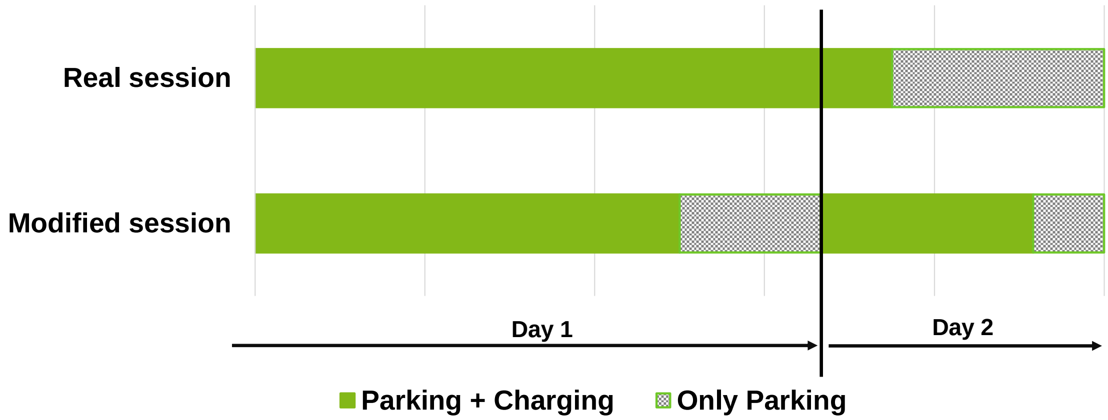



**Figure 5.3:** Split of charging sessions for the optimization - two different approaches

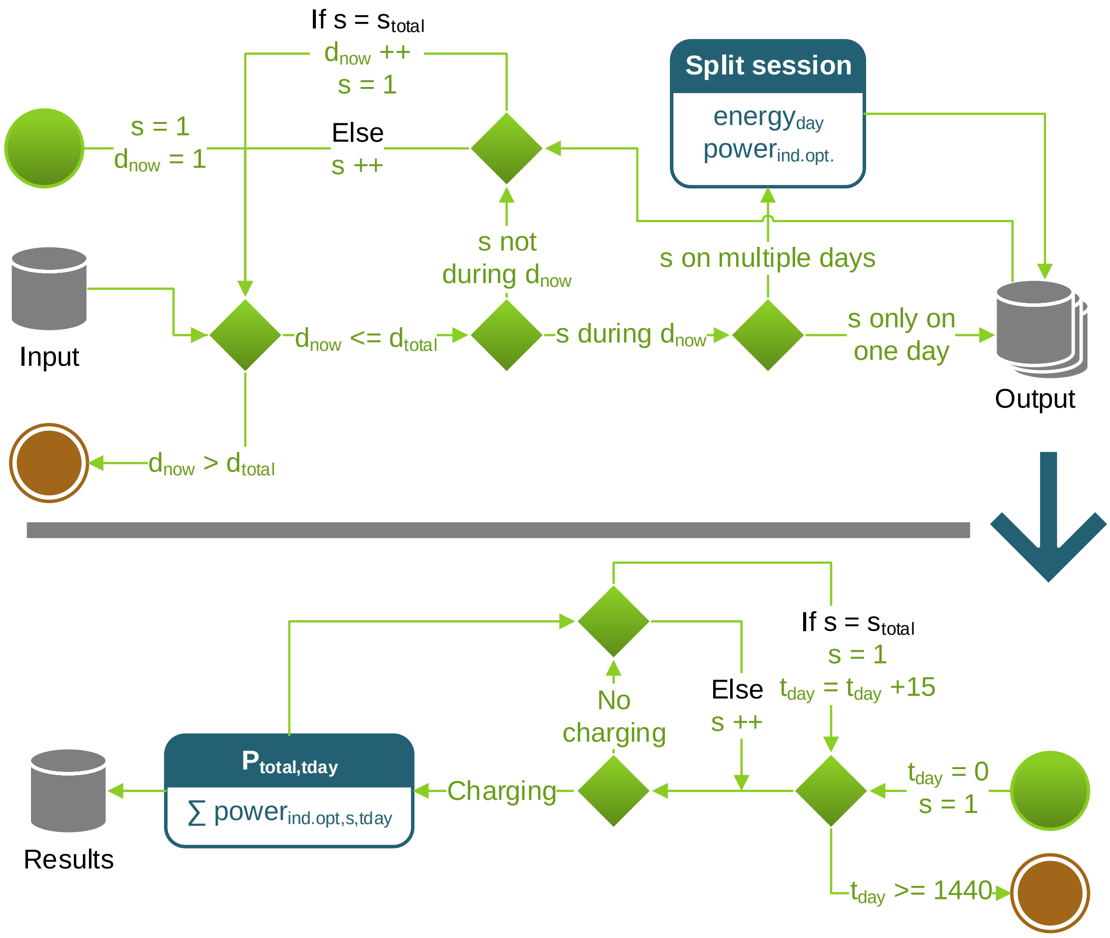
As an example, Figure 5.3 shows two splitting variants. In the first case (real session), a flexible charging process is split into a flexible and an inflexible part. In the second case (modified session), the charging time is divided between day 1 and day 2 in proportion to the parking time of the respective day. Both charging processes thus remain flexible. For better comparability of the results, the charging processes are split according to the modified session. Regardless of the optimization variant, the amount of energy consumed is therefore the same over the entire day. In principle, it should be noted that the analysis at this point could also have been carried out directly over the entire period. Particularly with regard to a further optimization approach (see Chapter 5.5), however, the limitation of the analysis time frame is necessary. The implementation of the optimization is again realized with the help of a Java-based tool and is shown in Figure 5.4. As in the initial scenario, the data are first read in via a SQLite database connection. As already described, the analysis should be done separately for each day, so that some charging sessions have to be divided into two charging processes. The energy drawn on each day ($energy_{day}$) can be calculated according to Formula 5.3. The total amount of energy ($energy_{total}$) is determined as a proportion of the parking time of one day ($time_{parking,day}$) to the total parking time ($time_{parking,total}$).

$$energy_{day} = energy_{total} * \frac{time_{parking,day}}{time_{parking,total}} \tag{5.3}$$

For optimization, the average charging power ($power_{ind.opt.}$) over the entire parking time must be determined as well. Like for the analysis of the original scenario, the charging power is again assumed to be constant and is calculated according to Formula 5.4. In comparison to the original case, the amount of energy obtained is not divided by the original charging time but by the parking time.

$$power_{ind.opt.} = \frac{energy_{day}}{time_{parking,day}} \tag{5.4}$$

Finally, a timer is used to check how many vehicles are present at what time, analogous to the analysis of the original scenario. The sum of the optimized charging capacities of all present vehicles ($P_{total}$) results in the optimized load at the respective time. The summary and evaluation of the results is performed in the same way as the original scenario and can be taken from Section 5.3.




| | | | | | |
|---|---|---|---|---|---|
| $s$ | = | Current charging session | $energy_{day}$ | = | Req. energy for charging day |
| $s_{total}$ | = | Total charging sessions | $power_{ind.opt.}$ | = | Optimized charging power |
| $d_{now}$ | = | Day of charging session | $P_{total}$ | = | Aggregated charging power |
| $d_{total}$ | = | Total days | $t_{day}$ | = | Daytime in minutes |

**Figure 5.4:** Simplified illustration of the individual optimization

The presented optimization method represents a simple approach to influence the load curves. If it is possible to obtain information from the customers about their expected parking times and the amounts of energy to be charged, the optimization can be carried out within a single charging point. An exchange between individual charging points as well as a higher-level control mechanism are not necessary. For this reason, however, there is also a weakness in the optimization which is shown in Graphic 5.5. Due to the fact that all charging events are optimized independently, the optimum of the aggregated charging processes can be different. In the example shown, car 1 and car 2 charge at different times in the original case. In the optimized case, the charging time of car 1 is extended with correspondingly lower power. The charging process of car 2, on the other hand, is inflexible so that the charging behavior remains the same. Due to the resulting overlap of both charging processes, the peak of the resulting total load in the example shown is therefore greater than in the original case.

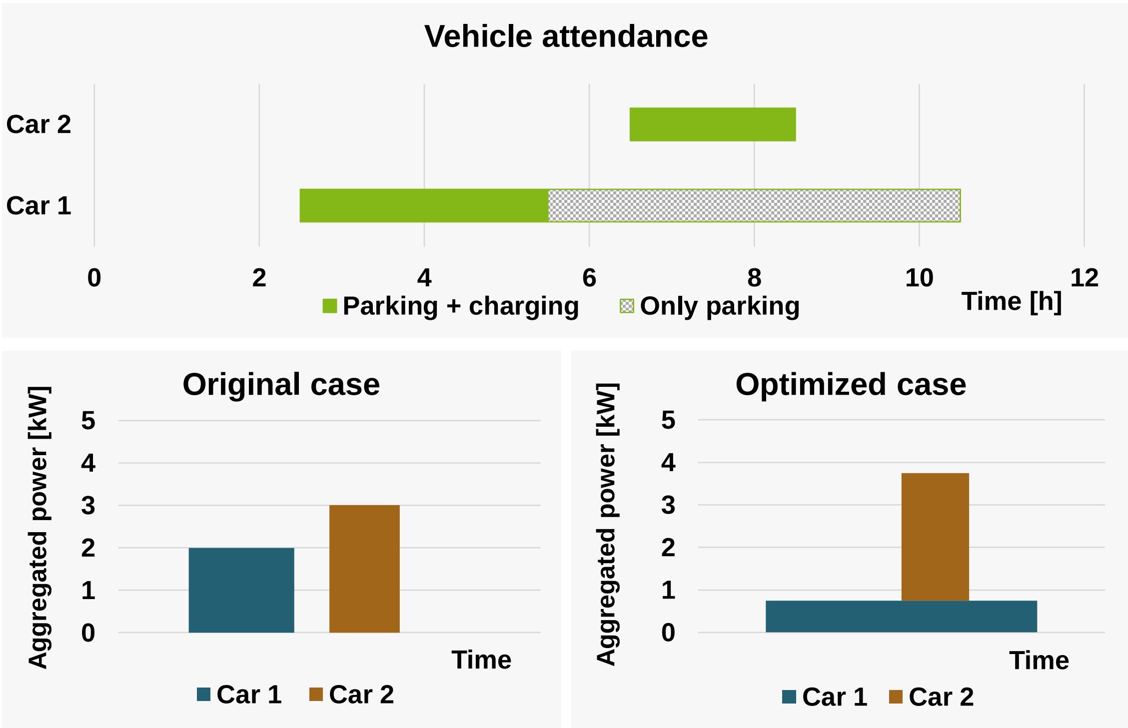



**Figure 5.5:** A weakness of the individual optimization - A higher resulting peak load is possible

It can be expected that the presented optimization method leads to a lower resulting peak load for a large number of combination. However, as the above example shows, the total load may also increase due to the optimization method that has been selected. To improve the results, a further optimization strategy is presented in the following section.

## 5.5. Field Optimization

In contrast to the individual optimization of all charging processes, the objective of field optimization is to minimize the peak load of the resulting total load curve. On the one hand, the weaknesses of individual optimization shown in Graphic 5.5 can be removed. On the other hand, it is possible to further reduce the peak loads of the entire system by a smart load shift.

Using an example scenario, Figure 5.6 shows how field optimization differs from the original scenario and from the individual optimization. In the original scenario shown on the left, it becomes clear that there are phases in which plenty of energy is needed, but there are also phases in which no energy is needed at all. In the scenario of individual optimization, the energy consumption is distributed more evenly over the observation period. Nevertheless, high peaks are still present. In the scenario of field optimization shown on the right, however, the peak has almost disappeared. The inflexible charging process of car 2 determines the peak load. In order to prevent this peak load from rising further due to parallel charging of the other vehicles, the charging process of car 1 and 3 is interrupted for this period. For this purpose, the power consumption is increased before and after car 2 is present.

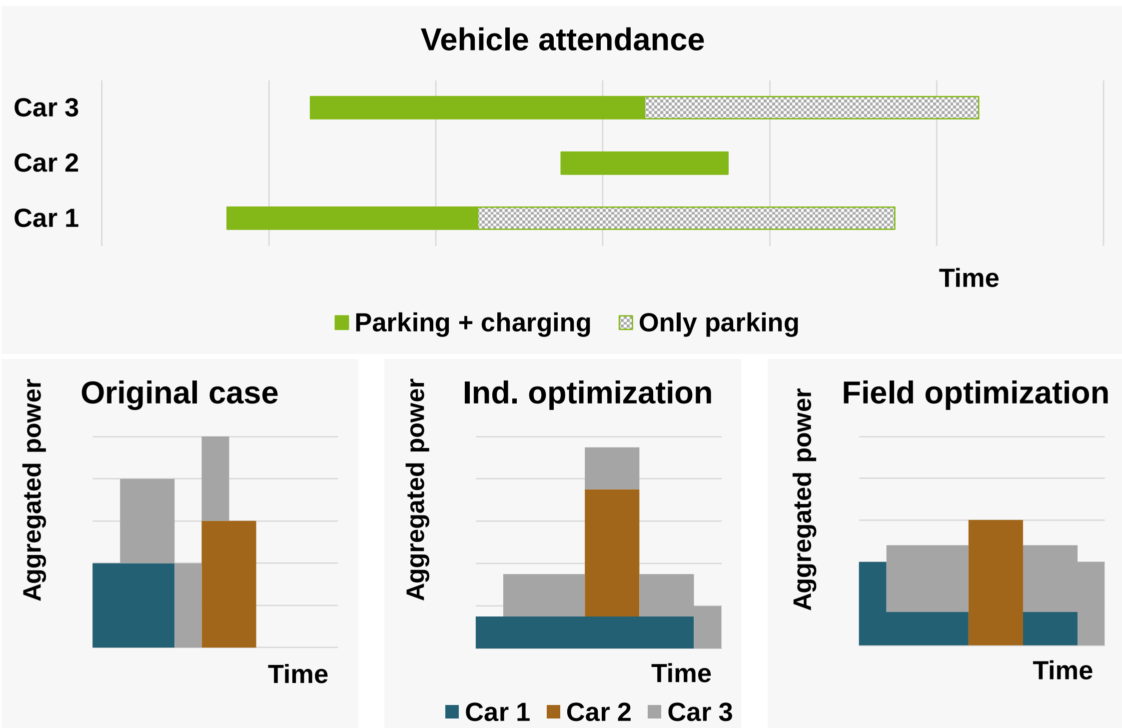



**Figure 5.6:** Comparison of the three charging strategies presented using an example scenario

Due to the fact that all parallel charging processes are highly related to each other, the complexity of the optimization increases significantly. For the example shown with only three vehicles, the optimal solution is comparatively easy to determine, but with an increasing number of vehicles it becomes more and more complicated to minimize the peak load. An optimization over the entire period of up to 20 months is therefore not feasible with the available resources, so that the optimum is determined once again separately for each day. However, the resulting error is only of minor importance. On the one hand, the flexibility of all charging processes is maintained by splitting according to the modified session (see Section 5.4). On the other hand, the number of affected sessions can be kept low by choosing the split time. As can be seen in the results Chapter 6.7, the majority of charging processes take place during the day, so that a splitting is carried out at 3 o'clock respectively 4 o'clock (for residential parking) in the morning.

The processing of the data takes place similar to the individual optimization in Java and can be taken from Section 5.4. For reasons of complexity, the optimization is outsourced to MATLAB. The charging time series, as well as information about the required amount of energy and the maximum power must be transferred accordingly for each vehicle.
In the first step, the boundary conditions of the optimization are defined. On the one hand, it has to be defined that each vehicle must have received the required amount of energy at the end of the charging session. On the other hand, the power consumption is only allowed to take place when the car is present. Additionally, it must be specified that the maximum power consumption cannot be exceeded and that it can never become negative. The objective function of the optimization finally represents the square function of the total load curve. Using the "fmincon" optimizer, the area below the objective function is minimized. A load distribution that would be at the same level over the entire day represents the absolute optimum. Due to the fact that the flexibility of the individual charging processes is limited, the absolute optimum can only be achieved theoretically. Nevertheless, the optimization ensures that peaks can be flattened as far as possible, since the area under the objective function becomes smaller as a result.
The optimized total load curves of all days considered are finally summarized again so that an average load profile can be obtained. The peak load of each individual day is read out as well. In the final step, the sum of all peak loads is compared with the peak load sum of the initial scenario and those of the individual optimization.

It should be mentioned again that the results are based on historical data. In this case it is therefore comparatively easy to determine an optimal charging strategy. A much greater challenge, on the other hand, is the implementation of the optimization in a real system. In addition to the information of the customers about their parking time, the user behavior must also be analyzed as well. In order to achieve an optimal result, the arrival times and the required energy amounts must be predicted as accurately as possible. The results of this work therefore represent the potential of a perfect prediction.

# 6. Results

The results chapter is mainly divided into two sections. In a first step, the fundamental potentials of low power charging in the area of residential buildings are presented. The second step focuses on the analysis and optimization of real charging events. The effects of different optimization approaches with regard to load shifting of individual charging processes are presented separately.

## 6.1. Low Power Charging at Residential Buildings

The results for low power charging at home are strongly dependent on the given infrastructure and the behavior of the users. It is therefore difficult to make a general statement about the Quality of Service (QoS) of a charging system. Using an example scenario based on average values, the results presented below can be taken as a baseline. By varying individual parameters in the simulation of different charging processes, their influence on the overall result is also examined more closely.

### 6.1.1. Range Calculation

For the calculation of the results, it is assumed that each apartment has 20 percent free capacity for future installations (see DIN-18015-1). Based on this assumption, it can be assumed that the building connection must also be designed for a 20 percent higher load. If these free capacities are used exclusively for the installation of charging points and if an average consumption is assumed, energy can be provided for the ranges shown in Table 6.1.

As expected, the range increases with a longer charging time. Also with an increasing number of apartments the potential of the total range increases. The range per apartment, however, is decreasing with an increasing number of apartments (see Figure 6.1). The reason for this is the simultaneity factor described in Chapter 4.1.6.

**Table 6.1:** Possible ranges based on charging times and number of apartments

| | 8 h charging total distance | 12 h charging total distance | 16 h charging total distance |
|---|---|---|---|
| **Building with 1 apartment** | 108 km | 161 km | 214 km |
| **Building with 5 apartments** | 305 km | 458 km | 611 km |
| **Building with 10 apartments** | 411 km | 617 km | 823 km |
| **Building with 20 apartments** | 536 km | 804 km | 1,072 km |
| **Building with 100 apartments** | 782 km | 1,173 km | 1,564 km |

Figure 6.1 shows that especially for buildings with a number of apartments smaller than 20, sufficient capacity should be available to recharge energy within 12 hours for the average range of 40 km/day. It should also be noted that with an increasing number of vehicles the probability increases that not all vehicles arrive and depart at the same time. Even if all vehicles have a 12-hours downtime, the time between the arrival of the first vehicle and the departure of the last vehicle might be much longer. As shown in Figure 6.1, buildings with 70 apartments can supply up to 70 vehicles with sufficient energy if the charging processes are evenly distributed over the entire day.

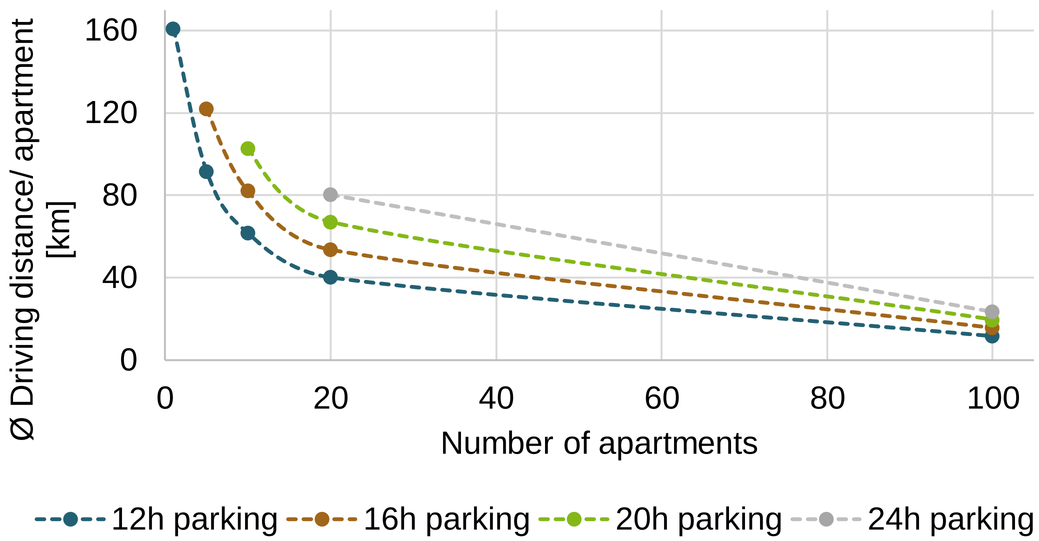



**Figure 6.1:** Available range per apartment

### 6.1.2. Simulation of Different Charging Events

The tool presented in Chapter 4.2 offers the possibility to obtain a quick overview of the Quality of Service (QoS) resulting from individual input parameters. Due to the multitude of possible combinations of the input variables, however, it is difficult to present a general result. As described in Section 4.2.5, an initial scenario is therefore defined first. Subsequently, different parameters are varied independently of each other in order to show their influence. The analysis always takes place for different numbers of apartments. It is assumed that each apartment owns one car which can be either electric or non-electric.
The initial scenario is shown in Figure 6.2. Especially for penetration rates of less than 25 percent, a charging system offers excellent service quality regardless of the number of apartments. However, with an increasing penetration, a decreasing QoS can be observed especially for larger buildings with many apartments.

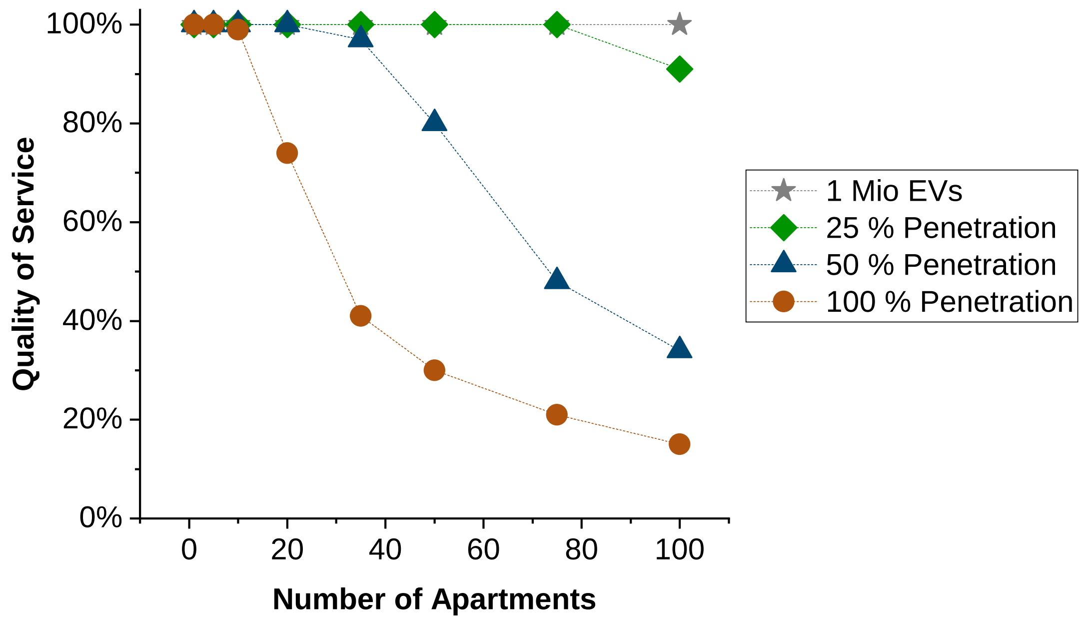
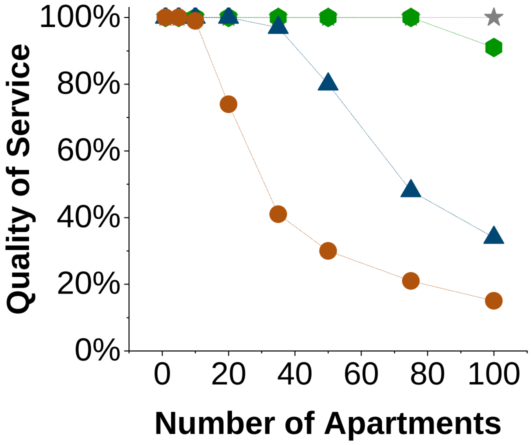
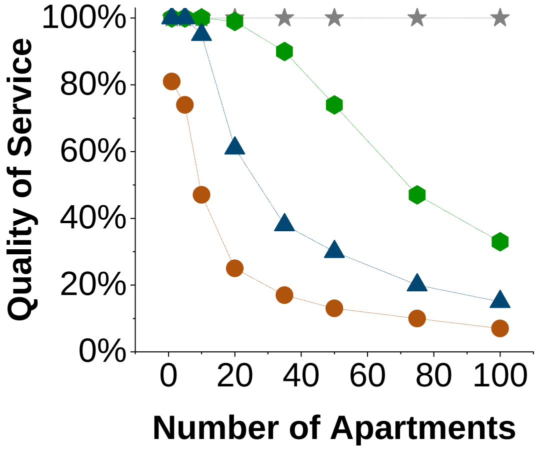



**Figure 6.2:** Quality of service - initial scenario

Based on the initial scenario, the effects of a reduced free capacity are presented in the next step. The left graph in Figure 6.3 shows once again the initial scenario where 20 percent free line capacities were assumed. On the other hand, the right graph shows the results of a reduced free line capacity to 10 percent. Especially for large buildings with a high number of charging points a decrease of the QoS is noticeable. For smaller and medium-sized buildings, however, the QoS remains on a high level even for higher penetration rates of electric cars.




(a) Initial scenario




(b) 10 % free capacity

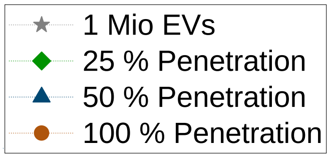
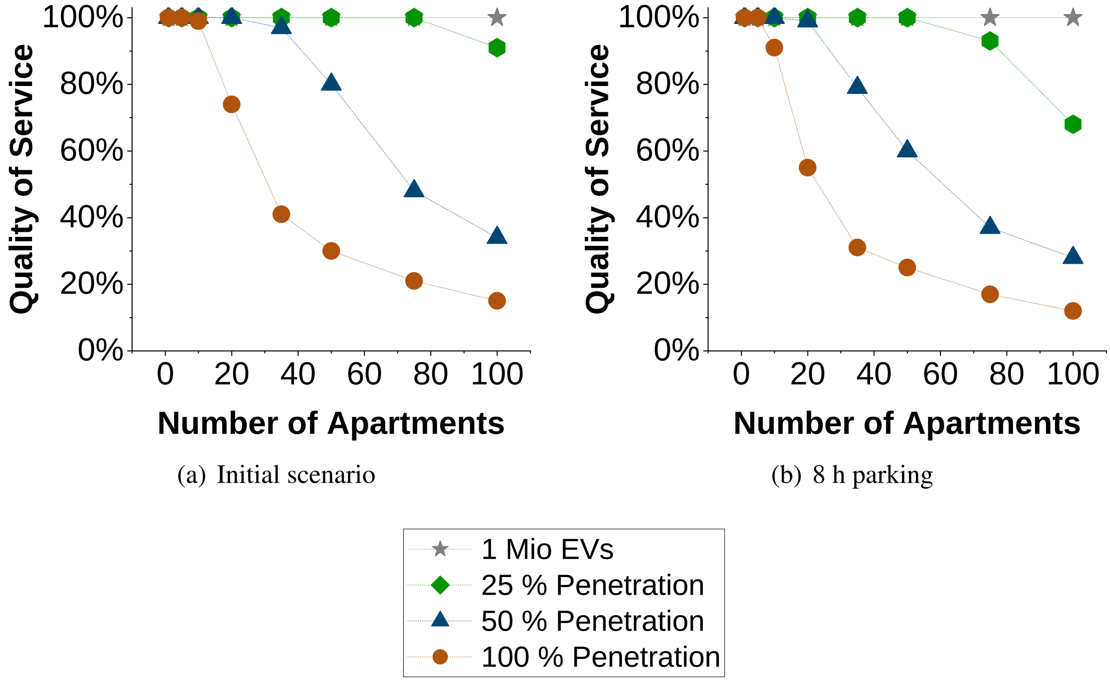



**Figure 6.3:** Impact of a minor free capacity

The effects of a reduced charging time are shown in Figure 6.4. For better comparability, the initial scenario is again shown in the left graph, which assumes an average parking time of 10 hours. The graph on the right side finally shows the results of a reduced parking time of 8 hours on average.

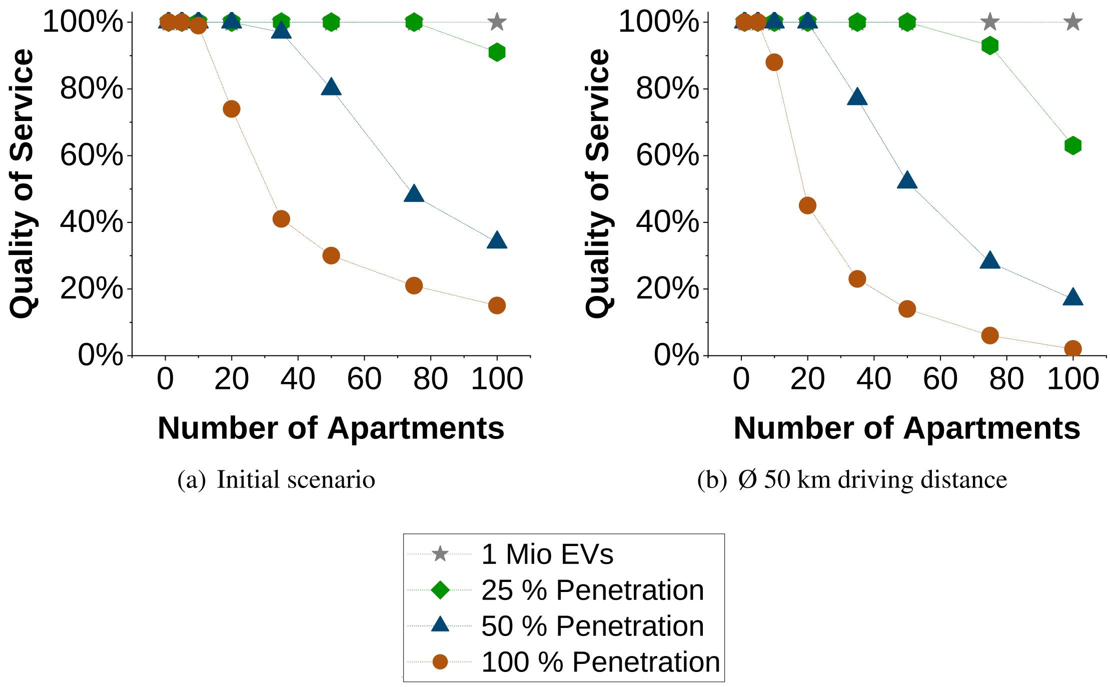
In a further step, a variation of the average daily driving distance is examined more closely. The results are shown in Figure 6.5. While the left graph shows the initial scenario with an average driving distance of 40 km, the right graph shows the results of an average driving distance of 50 km.




(a) Initial scenario

(b) 8 h parking

**Figure 6.4:** Impact of a reduced parking time

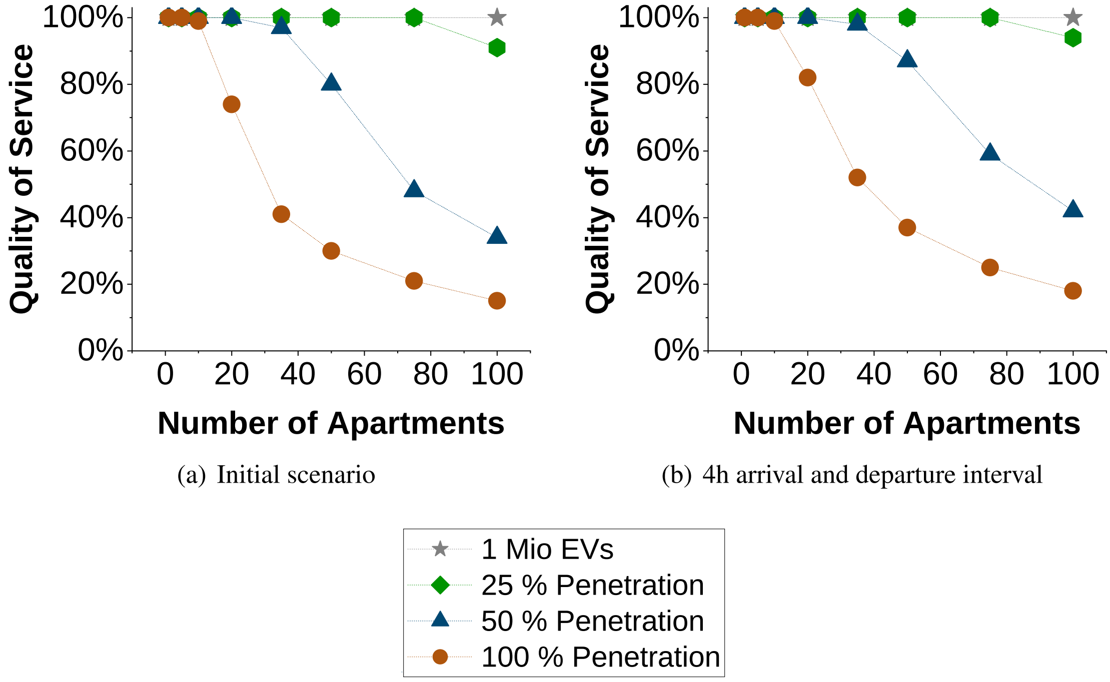



(a) Initial scenario

(b) Ø 50 km driving distance

**Figure 6.5:** Impact of a longer distance traveled

Finally the effects of varying the arrival and the departure times are shown in Figure 6.6. In both cases, the average parking time is 10 hours. In the initial scenario, it is assumed that all vehicles arrive and depart within a 2-hour interval. The right graph shows the results where a 4-hour arrival and departure interval is assumed. It can be seen that a larger interval can slightly improve the QoS.




(a) Initial scenario

(b) 4h arrival and departure interval

**Figure 6.6:** Impact of a longer arrival and departure interval

## 6.2. Analysis and Optimization of Real Parking and Charging Data

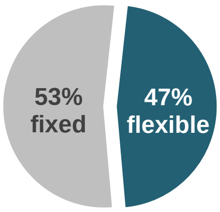
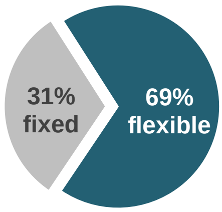
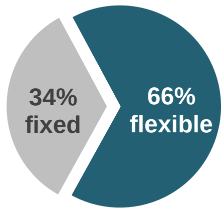
The results are based on around 25,000 data sets of historical charging events of EVs. The data were collected by two Finnish companies in the area of Helsinki and were gathered between 2017 and 2019. In addition to the charging time, parking times as well as the amount of energy consumed are known. The data only consider normal charging points (power not higher than 22 kW) with an average charging capacity of less than 3 kW.
In the following, a basic description of the data sets is given. For this purpose, the average amounts of charged energy are shown and the average parking and charging times are compared with each other. Subsequently, the results of the flexibility analysis are presented in more detail. In addition to the presentation of the load curve of the uncoordinated real charging scenario, the results of the two optimizations are shown as well. The analysis is divided into three categories - public, commercial and residential charging. For public and commercial car parks, the data of several locations are available. Due to the fact that parking times vary greatly from location to location, a location-dependent analysis is carried out.

### 6.2.1. General data analysis

An overview of the data used is given in Table 5.1 as well as in Table 6.2. It can be seen that the average parking time for all three categories is far above the average charging time. The high proportion of flexible charging processes of about 2/3 in commercial and residential car parks already indicates a high potential for an optimization. For public car parks, the portion is slightly lower at just under 50 percent, however, a significant reduction of the peak load can be expected as well.

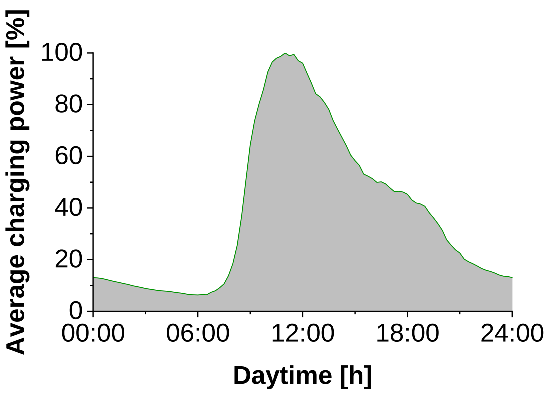
**Table 6.2:** General data analysis

| | Public parking lots | Commercial parking lots | Residential parking lots |
|---|---|---|---|
| **# Charging sessions** | 20,382 | 4,664 | 449 |

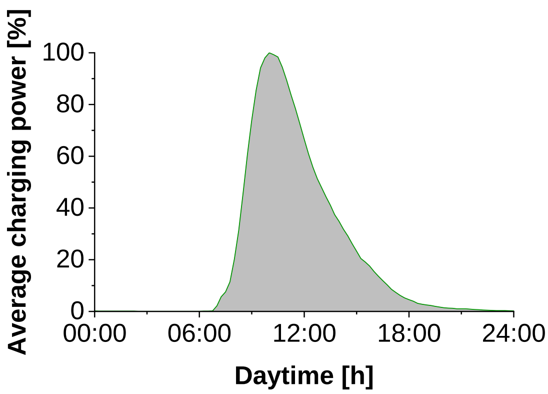
| | | | |
|---|---|---|---|
| **Ø - Parking duration [h]** | 5:05 | 6:14 | 11:13 |
| **Ø - Charging duration [h]** | 3:03 | 3:42 | 4:49 |
| **Flexible sessions** |   |   |   |
| **Ø - Energy consumed [kWh]** | 6.39 | 5.88 | 5.22 |
| **Ø - Charging power [kW]** | 2.66 | 1.59 | 1.09 |

### 6.2.2. Load Profile - Real Charging Data

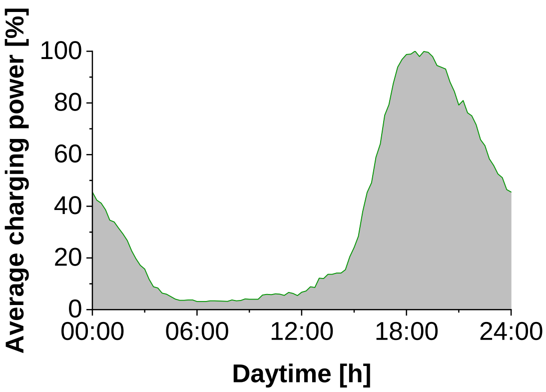
The summed load profiles are displayed for all three categories considered in Graphic 6.7. By adding all load profiles, an average load profile can be taken from the figure. Of great interest are especially the times at which the peaks occur as well as the general progression of the load curve.




(a) Public charging




(b) Commercial charging




(c) Residential charging

**Figure 6.7:** Load profile - real charging data

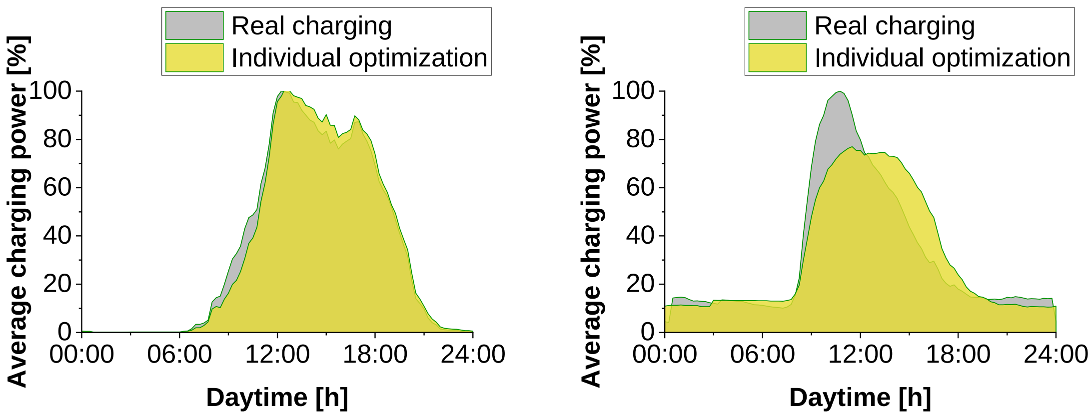
The energy consumption of public charging stations is essentially distributed over the entire day. Most of the energy is drawn between 9 am and 9 pm. The highest load can be seen at lunchtime. For commercial charging, the peak is reached at around 10 o'clock in the morning. The majority of the energy consumption takes place between 9 am and 1 pm. Consequently, there is only a relatively short charging interval. The situation is different, however, with the course of residential charging. On the one hand, the energy consumption is distributed over a longer period, on the other hand, the peak is not reached until 6 o'clock in the afternoon.

### 6.2.3. Individual Optimization

In the following the results of the individual optimization are shown. For this purpose, they are compared with the uncoordinated real charging data. On the one hand, the summed total load curves are compared with each other. On the other hand, the peak loads of all considered days are summed up and the average improvements are shown.
For a better overview, only the results of the selected locations are presented in this section. The selection includes all results with special characteristics. The analysis of all other (larger) sites can be found in Annex A.8.

### Public Parking Lots

First, the total accumulated load of the real charging behavior is compared with the individual optimization. Graphic 6.8 shows two different locations. For R-Parking the average parking time is less than 2 hours, for K-Parking it is about 7 hours. While the optimized load curve of the parking garage R-Parking deviates only slightly from the real load curve, K-Parking shows a clear load shift into the afternoon.




(a) R-Parking (b) K-Parking

**Figure 6.8:** Individual optimization - load profile - public charging

A closer look at the average peak loads of all the days considered delivers a similar result, which are presented in Figure 6.9.

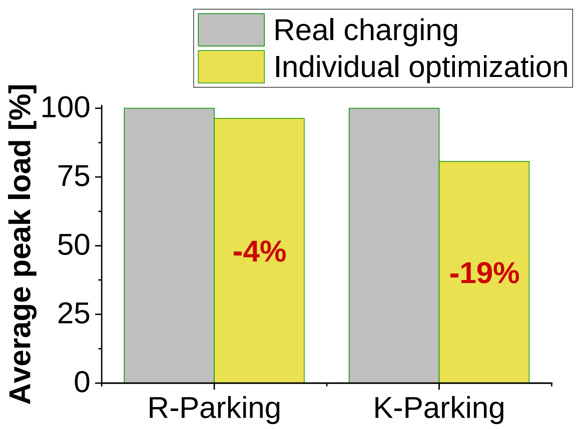



**Figure 6.9:** Peak load reduction - public charging

It can be observed that the average peak load for R-Parking can only be reduced slightly by 4 percent. For K-Parking, the change is again significantly higher with almost 20 percent. The average peak loads of the uncoordinated real charging data serve as the base case for the consideration.

In total, five larger sites of the public charging category are examined in more detail. Figure 6.10 shows the results of the individual optimization of all considered locations as a function of the parking duration. The presented peak load reduction is to be interpreted as the peak load reduction which is performed by the optimization compared to the peak load of uncoordinated real charging scenario. The dashed line shows that there is an approximately linear correlation between the parking time and the potential for improvement.

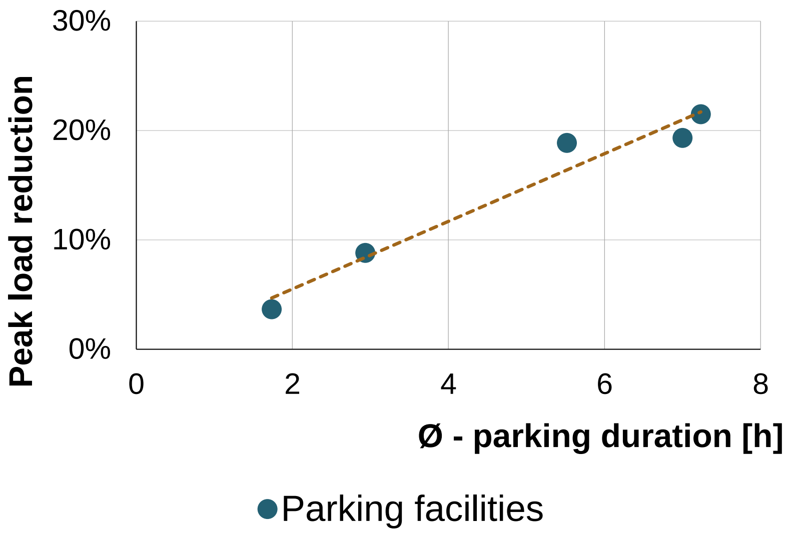
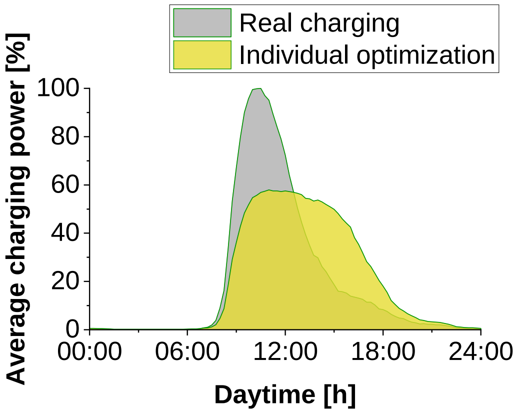


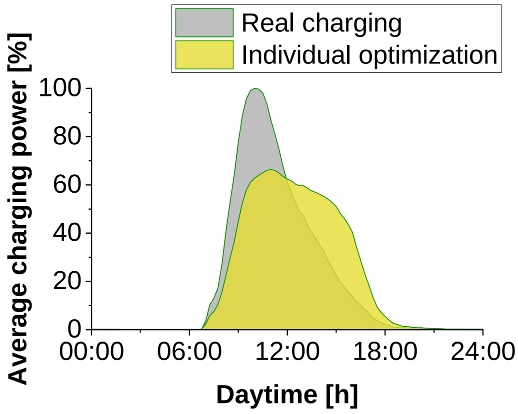

**Figure 6.10:** Peak load reduction potential as a function of parking time (1)

### Commercial Parking Lots

Analogous to the public charging, the summed total loads of the uncoordinated and the optimized scenario of the commercial charging are first compared with each other. At both locations shown, the average parking time is between 6 and 7 hours. As can be seen in Figure 6.11, without the optimization, a large part of the energy consumption takes place in the morning. The results of the individual optimization, however, show a more even distribution of the load over the morning and the afternoon.




(a) I-Parking




(b) H-Parking

**Figure 6.11:** Individual optimization - load profile - commercial charging

Looking at the average peak loads a high optimization potential of individual optimization can be seen. With reference to Graphic 6.12, peak loads can be reduced by about 30-40 percent on average.

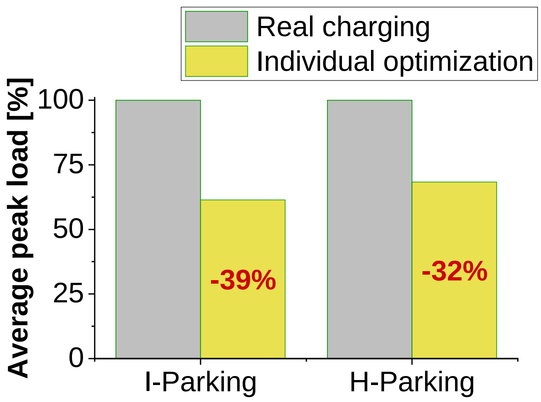
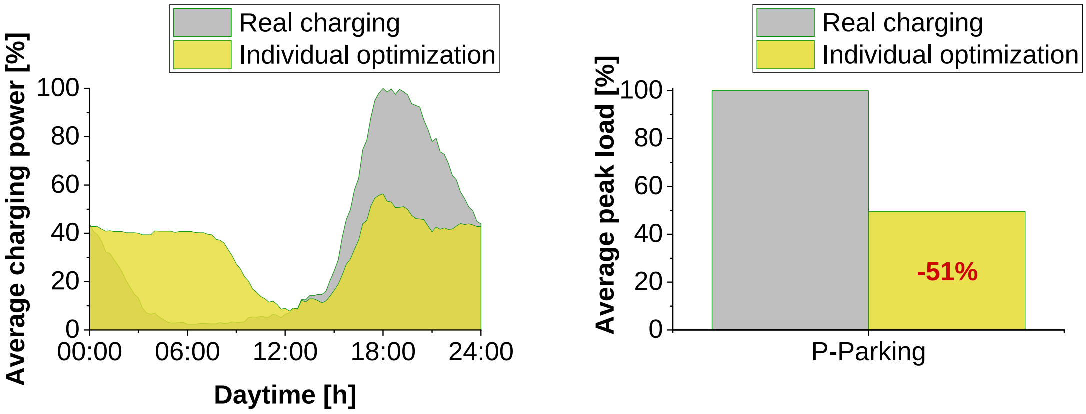



**Figure 6.12:** Peak load reduction - commercial charging

**Residential Parking Lots**

Due to the fact that for the analysis only data of one location were available, a comparison of several parking facilities is not possible in this case. Graphic 6.13 therefore only shows the results of the P-Parking location. The figure on the left shows the total loads once again. In the uncoordinated real scenario, a large part of the energy consumption takes place in the evening and in the first half of the night. The

optimized scenario, on the contrary, depicts an almost uniform energy consumption over the entire day.
The right diagram shows the average peak load reduction. It can be seen that the average peak load can be more than halved by the optimization.




(a) Load profile - residential charging

(b) Peak load reduction - residential charging

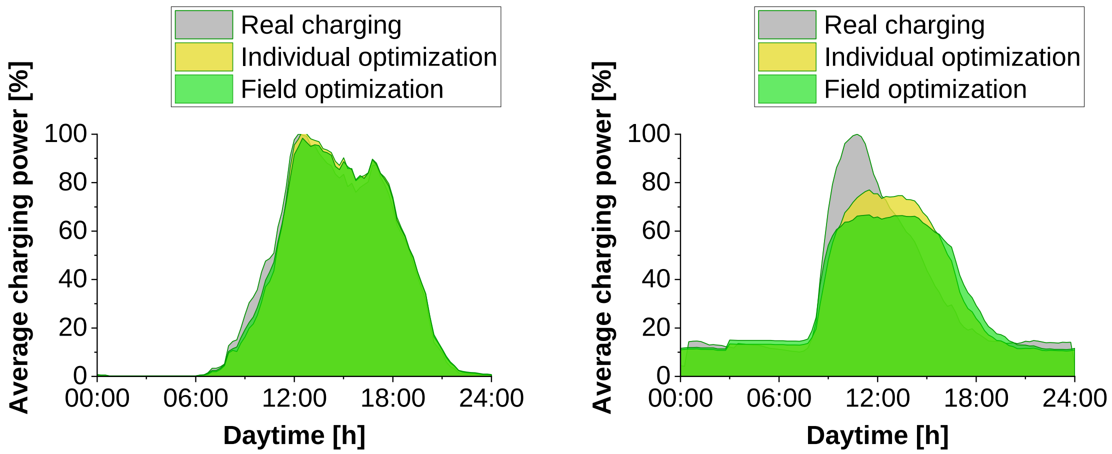
**Figure 6.13:** Individual optimization - residential charging

### 6.2.4. Field Optimization

The results of the field optimization are presented analogously to the results of the individual optimization. For better comparability, both the data of the uncoordinated real scenario and the data of the individual optimization are listed in the figures as well. Once again, only selected locations are considered in this chapter. All other (larger) locations can be found in Annex A.8.

#### Public Parking Lots

Looking at the total accumulated loads for R-Parking, only minor changes can be seen in comparison with the individual optimization (cf. Figure 6.14). For K-Parking, on the other hand, a clear difference is visible for all three considered variants. The effect of the load shift into the afternoon, which already occurs due to the individual optimization, is further reinforced by the field optimization.




(a) R-Parking (b) K-Parking

**Figure 6.14:** Aggregated optimization - load profile - public charging

Once again, the average peak loads are also considered more closely. For R-Parking, the improvements compared to K-Parking are again significantly lower (cf. Figure 6.15). In both cases, however, there is a clear improvement over individual optimization.

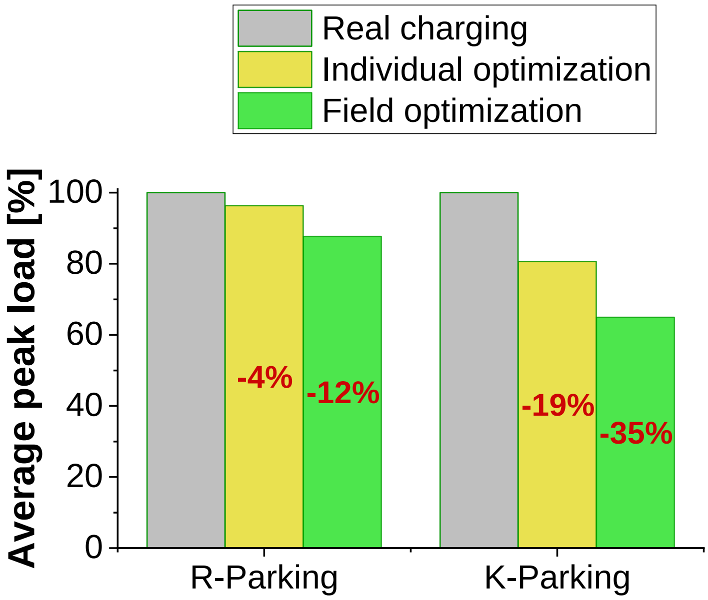



**Figure 6.15:** Peak load reduction - public charging

The peak load reduction due to the respective optimization of all public locations are also evaluated once again in relation to the respective parking time. The values which are shown in Figure 6.16 represent the relative peak load reduction of the optimizations compared to the peak load of the uncoordinated real scenario. As can be seen, a linear dependency exists between the parking time and peak load reduction of the optimizations.

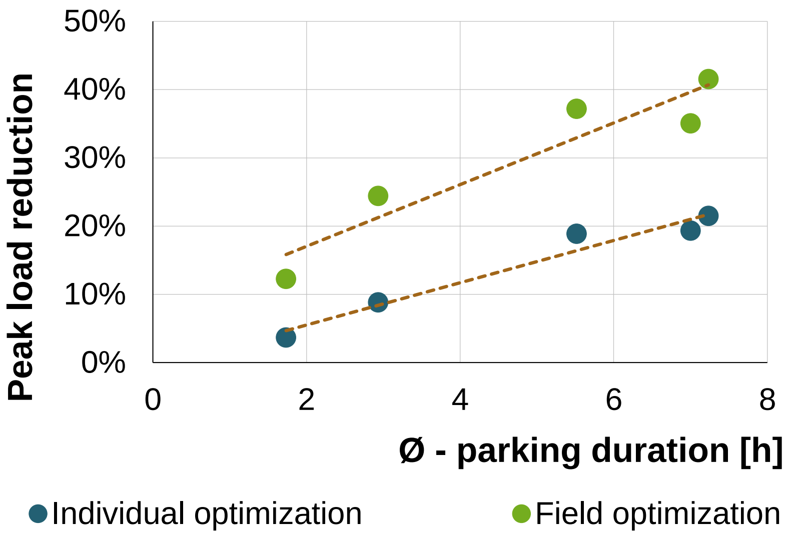
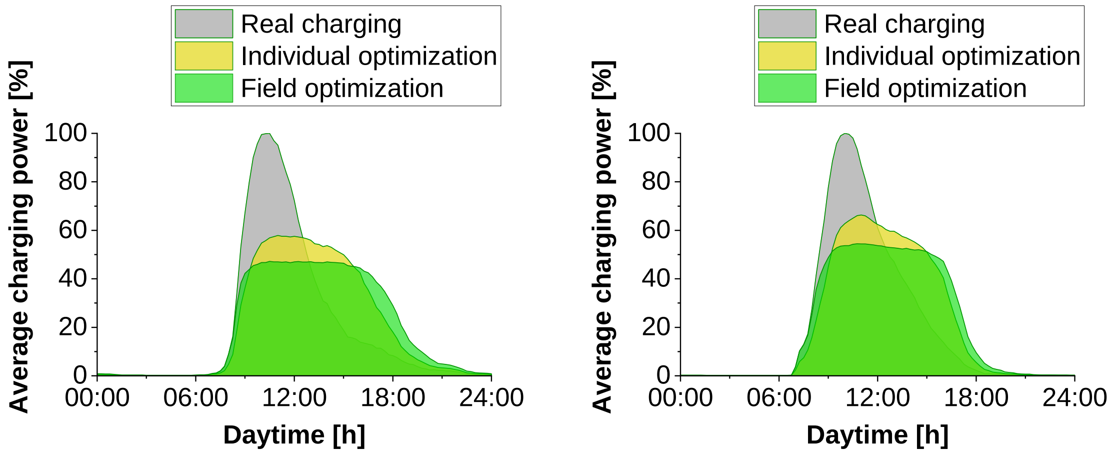



**Figure 6.16:** Peak load reduction potential as a function of parking time (2)

### Commercial parking lots

The results of the facilities I-Parking and H-Parking are shown in Figure 6.17. In both cases it can be seen that the field optimization further reinforces the results of the individual optimization. A more uniform energy consumption can be seen.




(a) I-Parking (b) H-Parking

**Figure 6.17:** Field optimization - load profile - commercial charging

The average peak loads which are shown in Figure 6.18 can be further reduced by the field optimization as well. Overall, a peak load reduction at both locations by about 50 percent on average is possible.

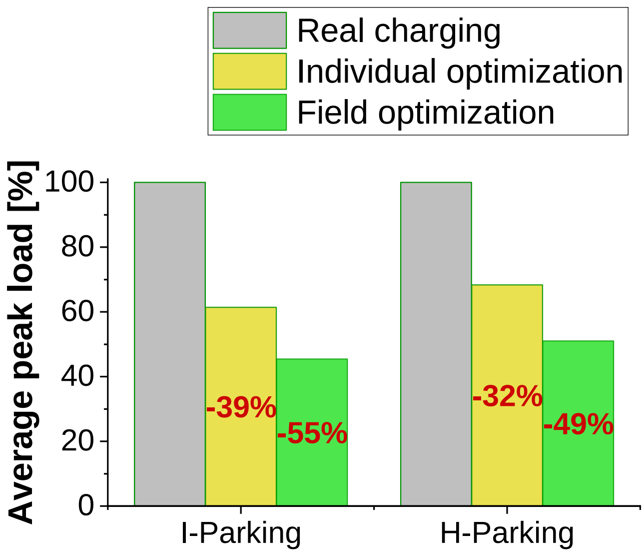
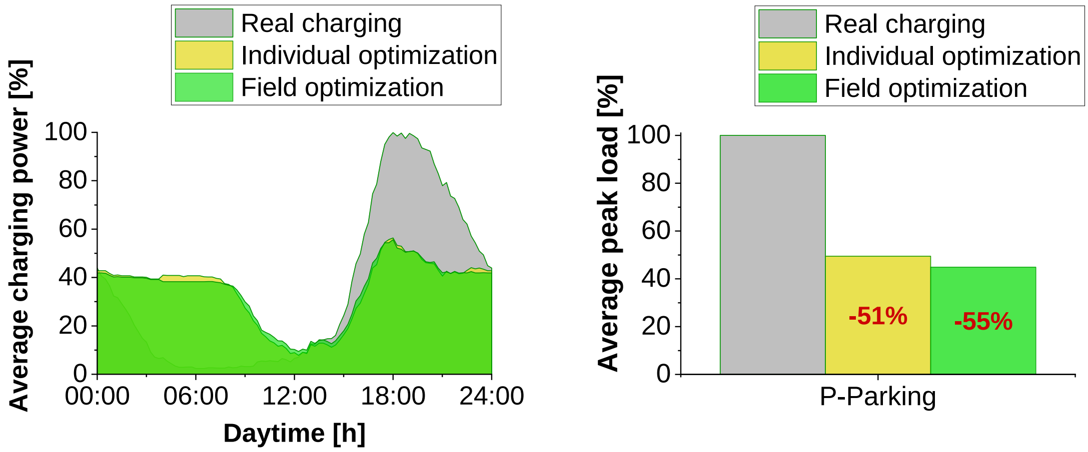



**Figure 6.18:** Peak load reduction - commercial charging

### Residential Parking Lots

Figure 6.19 presents the results of P-Parking. It is noticeable that the accumulated total load curves as well as the average reduction of the peak load deviate only slightly from those of the individual optimization.




(a) Load profile - residential charging (b) Peak load reduction - residential charging

**Figure 6.19:** Field optimization - residential charging

# 7. Analysis of Results

The analysis of the results takes place analogously to the presentation of the results. In a first step, the potentials of low power charging for residential buildings are discussed. In a second step, the results of the optimization approaches are the main focus. Therefore location-dependent strengths and weaknesses are analyzed more closely.

## 7.1. Low Power Charging at Residential Buildings

Low power charging in residential buildings offers a reliable solution to install new charging infrastructures in a cost-efficient in many cases. In the following, the results of the range calculation tool will be discussed briefly. Subsequently, the influences of a varying parameter input are discussed in more detail. Especially with regard to the geographical location (urban/rural) results can be interpreted differently. In a final evaluation of the simulation tool, both strengths and weaknesses of the tool are pointed out.

### 7.1.1. Range Calculation

The range calculation tool allows real estate owners to get a quick overview of the potential of their own infrastructure. However, the results presented can only provide a rough orientation, as individual user behavior is neglected in the calculation. In case that only 80 percent of the capacity of the building connection is used so that 20 percent are available to a possible charging system, the potential is particularly high for small and medium-sized buildings. Especially in the transition phase a great potential exists, due to the fact that only a part of the population owns an EV. The final decision for or against the installation of a charging system should not be made on the basis of the range calculation tool. A more detailed impact analysis of individual user behavior patterns, however, is highly recommended.

### 7.1.2. Simulation of Different Charging Events

The results of the simulation tool intensify the results of the range calculation tool. By varying different input parameters to represent an individual user behavior, the relevance of the tool is significantly higher. However, it can be seen that the prediction of the range calculation that low power charging is a promising option especially for small buildings is confirmed by the simulation as well. It turns out that the approach of low power charging can achieve great success. Especially in the transition phase in which the proportion of EVs is still comparatively low high QoS rates are possible for all kinds of building. With an EV penetration rate close to 100 percent, buildings with less that 10 apartments still can offer a great charging quality. Nevertheless, with a higher penetration rate it becomes apparent that the use of such a system is strongly dependent on the behavior of the users and the free capacity of the building. Especially longer distances have a negative influence on the QoS. The impact of the parking duration, as well as the dispersion of the individual parking sessions, is slightly smaller. However, it must be taken into account that the influences of the different parameters can reinforce or weaken each other.
For larger buildings with a high number of EV charging points, low power charging is only an option under certain conditions. Of course, a higher QoS can be achieved at any time by upgrading the corresponding building connection, which, however, would be in line with higher costs. As an alternative, the environment should therefore be analyzed first. As described in Chapter 2.4.1, the average distances traveled in urban areas are much shorter than in rural areas. Since large buildings are more likely to be found in urban areas, a lower energy requirement is conceivable.
In summary, it can be stated that the existing infrastructure can provide a great QoS for many cases. Especially for the transition period, where the penetration rate of EVs is still quite low, excellent results can be expected. With a penetration rate close to 100 percent upgrades in the infrastructure cannot be completely ruled out. However, an increasing spread of charging points also increases the probability that only part of the daily energy needed has to be charged e.g. at the residential building. As a result, a lower energy requirement leads to an increase in the QoS of the charging system.

It should also be noted that the tool presented is a compromise between individual behavior and complexity. Although input parameters vary within an interval, all charging processes follow a certain pattern. For example, if there are people who frequently have to work at night and therefore charge their EV during the day, it is difficult to represent them with the tool. In contrast, however, there is a risk that the tool will become too complex for the real estate owner. On the one hand, the question arises whether it is possible to obtain information from the tenants about their charging behavior. On the other hand the real estate owner might not be interested to spend a lot of time for processing all information. Especially considering a certain fluctuation of the tenants, the results are generally subject to some changes.

## 7.2. Analysis and Optimization of Real Parking and Charging Data

In the following, both the characteristics of the real charging behavior as well as the optimization potentials are analyzed in more detail.
On the one hand, the average parking and charging times are of great interest. On the other hand, the average load profiles and the peak loads are evaluated more precisely. Optimization potentials resulting from the various optimization approaches are discussed and evaluated depending on the location. Finally, the general optimization procedure is evaluated within the framework of this work. Difficulties and challenges in particular will be discussed in more detail.

### 7.2.1. General Data Analysis

For all three categories used (public, commercial, residential), the high degree of flexible charging processes shows a high optimization potential. Comparing the average parking times with the average charging times, public and commercial data are at a similar level. The average parking time here is 2 - 2.5 hours longer than the average charging time. The situation is different for residential charging. On average, the parking time exceeds the charging time by more than 6 hours. Also interesting to observe is the length of the average parking time. With 11:13 hours, the average parking time is above the 10 hours assumed in the simulation tool (see Chapter 4.2.5). Based on these data, the potential of low power charging at home is therefore even slightly higher. For the results of the residential charging, however, it should be taken into account that only a few charging points formed the basis of

the analysis. For an improved validation, the analysis should be repeated in future works on the basis of a larger data set.
Expecting that EV owners charge their vehicles overnight at home and also during the day at work or at other public car parks, the average energy consumption is about 11.3 kWh. According to the calculated charging losses of 11 percent (see Chapter 4.1.3) and the average consumption of 19.6 kWh/100km (see Chapter 4.1.2), the average driving distance is about 51.3 km/day. A comparison of these values with the average daily distance traveled by all vehicles in Finland of 50 km/day [33] shows that the data used are representative for the whole country. It should be noted that the statistic does not take into account any days on which no charging has taken place, therefore the actual values are slightly lower. As described in Section 2.4.1, the average distances traveled in urban area are lower than in the rural area. Due to the fact that all data come from the metropolitan region of Helsinki, a range below the national average is not surprising.

### 7.2.2. Load Profile - Real Charging Data

All three load curves presented in Chapter 6.2.2 show a different profile. The approach of carrying out a separate analysis for public, commercial and residential parking spaces thus proves to be correct. The commercial charging reaches its peak late in the morning. It can be assumed that most of the company's employees start working between 9 and 11 am, which explains a significant load increase during this time. Already before lunchtime a significant drop in the consumption of energy can be observed. However, it seems unlikely that many employees will leave work at this time of day. It seems much more realistic, however, that the cars are still parked but the batteries are already fully charged. This means that the peak loads could be reduced by a more evenly charging of the batteries throughout the entire working day.
Taking a look at the load curve of residential charging shows a similar curve, which is shifted by a few hours. From 3 pm in the afternoon a significant load increase can be observed, which reaches its maximum about 3 hours later. It can be expected that the majority of users come home from work at this time, connect their car to the power grid and won't unplug it until the next morning. By midnight, however, the load has already dropped by half compared to the peak load. At around 4 o'clock in the

morning, the lowest value is reached. It can be assumed that a more even energy consumption can also reduce the peak load here.
The profile of the public charging represents a combination of the two profiles explained above. A significant load increase during the general office hours can be seen again. In contrast to the commercial charging curve, the power consumption in the afternoon does not drop much. After 7 pm (analogous to the residential charging curve) a further drop in power consumption is noticeable. As a result, it should be noted that users of public parking facilities therefore use the charging stations for both private and business reasons.

### 7.2.3. Individual Optimization

The effects of load shifting which are realized by individual optimization are analyzed in more detail in the following. The analysis is carried out once again separately for the three defined charging categories.

**Public Parking Lots**
The results of the facilities R-Parking and K-Parking show that the optimization does not necessarily bring great advantages. For the R-Parking site, slight improvements are noticeable, but nevertheless the question arises whether the additional effort of an intelligent charging system exceeds the benefit of a lower peak load. At K-Parking, on the other hand, the peak load can be reduced by almost 20 percent. In the event that additional charging stations are required in the future, the number could be increased accordingly without large investments in infrastructure. If there is no need for additional charging stations, it would be possible to negotiate with the energy supplier about a lower capacity price.
As Figure 6.10 shows, there is a strong correlation between the optimization potential for improvement and the average parking time of the vehicles. If it can be expected that users park their vehicles only for a short period of time, for example in front of a grocery store, the installation of an intelligent charging system seems questionable. For a parking garage, for example at a trade fair site, where vehicles are parked for a longer period of time, a large optimization potential can be assumed. In this context, however, the user groups should also be included in the analysis as well. If it is to be expected that many customers will have a long journey,

the corresponding energy requirement will also be higher. Reducing the proportion of flexible charging sessions, the optimization must be questioned again.

**Commercial Parking Lots**

A similar result can be obtained for all analyzed locations of commercial charging. Due to the fact that many vehicles arrive within a short period of time, the peak of the real charging data is comparatively high. With the help of individual optimization, the energy consumption can be distributed more evenly over the entire working day. Compared to the results of the public parking lots, the reduction of the peak load for the commercial charging is considerably higher.

**Residential Parking Lots**

The highest potential of individual optimization can be found at resident charging points. Due to the long parking time of more than 11 hours, the peak shaving potential is significantly higher than, for example, for public charging. Similar to the commercial charging, many vehicles arrive at the charging station within a short period of time, so that a peak occurs in the early evening hours. However, the optimization makes it possible to shift a large amount of energy consumption into the night. As a result, an average peak load can be determined that is around 50 percent below the original load values.

### 7.2.4. Field Optimization

Analogous to the analysis of the individual optimization this chapter analyzes the effects of load shifting which are realized by field optimization. Once again the analysis is carried out separately for the aforementioned parking categories.

**Public parking lots**

The results for public charging show a similar situation than the results of the individual optimization. In case of R-Parking, a general load shift is only possible to a limited extent. Although the average peak load can be reduced by 12 percent significantly stronger compared with the individual optimization, the results of K-Parking are however far from being achieved. Due to longer parking times, a significant load shift can be seen at K-Parking. While the individual optimization was able to reduce the average peak load by 19 percent, the field optimization results in an improvement potential of 35 percent. For both locations, the results of field optimization are therefore significantly better than those of individual optimization. Due to the fact that the system is much more complex, a cost-benefit analysis should be carried out again. Graph 6.16 shows that all five locations analyzed show a clear dependence between the average parking time and the improvement potential of the optimizations. Before the implementation of an intelligent charging system can be considered, it is therefore highly recommended to first determine the parking behavior of the customers.

**Commercial parking lots**

All locations of commercial charging show a similar result which is not surprising, as working hours in many companies have a similar character. The high peak can already be significantly reduced by the individual optimization. Due to the field optimization a further reduction is possible. A comparison of the average peak loads shows that field optimization can reduce these by around 50 percent. The additional potential which can be used compared to the potential of the individual optimization is relatively small. It should therefore be discussed whether the individual optimization for commercial parking lots already achieves a satisfying result. Overall, however, there is a very high optimization potential for both optimization variants.

**Residential parking lots**

The results of the residential charging show a high optimization potential compared to the initial case. Compared to individual optimization, however, there are just minor advantages. While the individual optimization reduces the peak load by 51 percent, the field optimization can only improve the result by another 4 percentage points. It seems that due to the long parking time, the individual optimization already comes close to the absolute optimum.

### 7.2.5. Strengths and Weaknesses of the Different Approaches

All optimization alternatives represent a trade-off between the resulting benefits and the resulting additional efforts. In the case of individual optimization, it is necessary that all users provide information about their parking time and the desired amount of energy. It is hard to imagine that this would simply happen without a certain benefit for the customer. Consequently, an incentive system must be developed that motivates users to disclose their behavior. Furthermore, it should be considered that the individual optimization can under certain circumstances (see Section 5.5) cause a worse solution compared to the uncoordinated charging process. The field optimization can prevent this effect, but at the same time causes a much more complex calculation. In addition to information about the expected parking time and the desired amount of energy, it is also necessary to predict upcoming charging events. In case that only one vehicle has to be charged, a constant charging power over the entire day is the optimum. If, by contrast, it is known that other vehicles will arrive in the afternoon, the charging process for the first car should be completed in the morning. It should also be taken into account that drivers may deviate from their predicted parking times. For example, if a user indicates to park the car for 8 hours, the optimal solution might be that the vehicle is not charged until the second half of the parking period. In the event that the driver returns to the car after 4 hours to drive to a spontaneous appointment, the battery may still be completely empty. It is likely that the user experience will suffer greatly from this example. For improvement, it should therefore be considered to implement an additional minimum charging power for each vehicle in the system. Emergency rides could thus be covered, but the complexity of the charging system would continue to increase at the same time.

The results of the analyzed locations clearly show that the respective optimization should be evaluated anew for each location. If parking times are relatively short, the benefits of optimization are relatively small. If, in contrast, the parking times are very long, the individual optimization provides a large optimization potential, so that a more complex optimization can be dispensed with.

The technical requirements of the installed charging points must also be taken into account when deciding for or against field optimization. If all charging points are connected to the main connection as a star, an optimization is possible across all charging points. In the event that several bus topology branch off from the main connection point, a sub-optimization must take place for separately each bus.

### 7.2.6. Difficulties in the Optimization Process

Especially the complexity of the field optimization lead to problems with the chosen optimization algorithms. For days with a large number of charging events, the quadratic optimization used is not capable to present a solution within a reasonable period of time. For the evaluation the used data were sorted in a first run. In the final evaluation, only those data sets were included that could be completely optimized. As a result, the time series of the different locations are interrupted at some points. However, in terms of the significance of the results, there is no remarkable impact. The effect can nevertheless be observed in Graphic 6.14. When looking at the progress of the field optimization curve, a small jump at 3 o'clock in the morning can be observed. As described in Chapter 5.5, it is assumed that a day starts at this time of day. If a continuous time series were assumed, the field optimization would result in a more even progression at this point.

# 8. Conclusions and Future Work

## 8.1. Conclusions

From the results of this work it can be seen that the approach of low power charging has a very large potential and therefore can make an enormous impact on a quick expansion of further charging points. By an efficient use of the existing infrastructure it represents a resource-saving approach. Despite of longer charging times, excellent quality of services can be achieved, especially in the transition phase of road traffic electrification.

The analysis of the historical Finnish charging data shows that large optimization potentials exist even for low charging power approaches. Through an intelligent load shift, the average peak load of a charging system can be reduced by up to 55 percent. A comparison of location-dependent charging data shows that charging facilities at residential and commercial locations in particular have great potential. The results of the public locations, on the other hand, show a strong dependence on the average parking time. If the average parking time exceeds a duration of about three hours, however, high optimization potentials can be identified for both presented optimization approaches as well. The average driving distances can be derived from the average amount of charged energy. Due to the fact that these values correspond to the general national average of Finland, the results are very valuable.

## 8.2. Future Work

To predict the load profiles of real estate buildings, a smart meter must first be installed. Due to regulatory requirements, solutions from Finland cannot be transferred directly to Germany. A corresponding hardware and software adaptation is therefore often necessary.

Knowledge of user behavior is essential for using the optimization potential. Since the results of this work are based on historical data, a complete knowledge is available. For real-time optimization, however, it is necessary to make predictions that are as accurate as possible. An app-based implementation would be imaginable. In the event that the user provides information about the planned charging behavior, lower energy prices could be offered in return. The design of a corresponding incentive system should be studied in future works.

A more precise analysis of customer data is also conceivable. If a customer's charging processes always follow the same pattern, peak load times can be predicted. Consequently, also the expected length of the parking time can be deduced. It is therefore desirable to develop an intelligent algorithm that can make increasingly accurate predictions as the number of charging sessions of a user increases.

Another point that should be considered in future works is the further development of the presented simulation tools. One conceivable option would be an additional implementation of the building load profile. At times with low building load levels, more power can be made available to a charging system. An increase in the quality of service is therefore conceivable.

# A. Appendix

## A.1. Example fast charging map

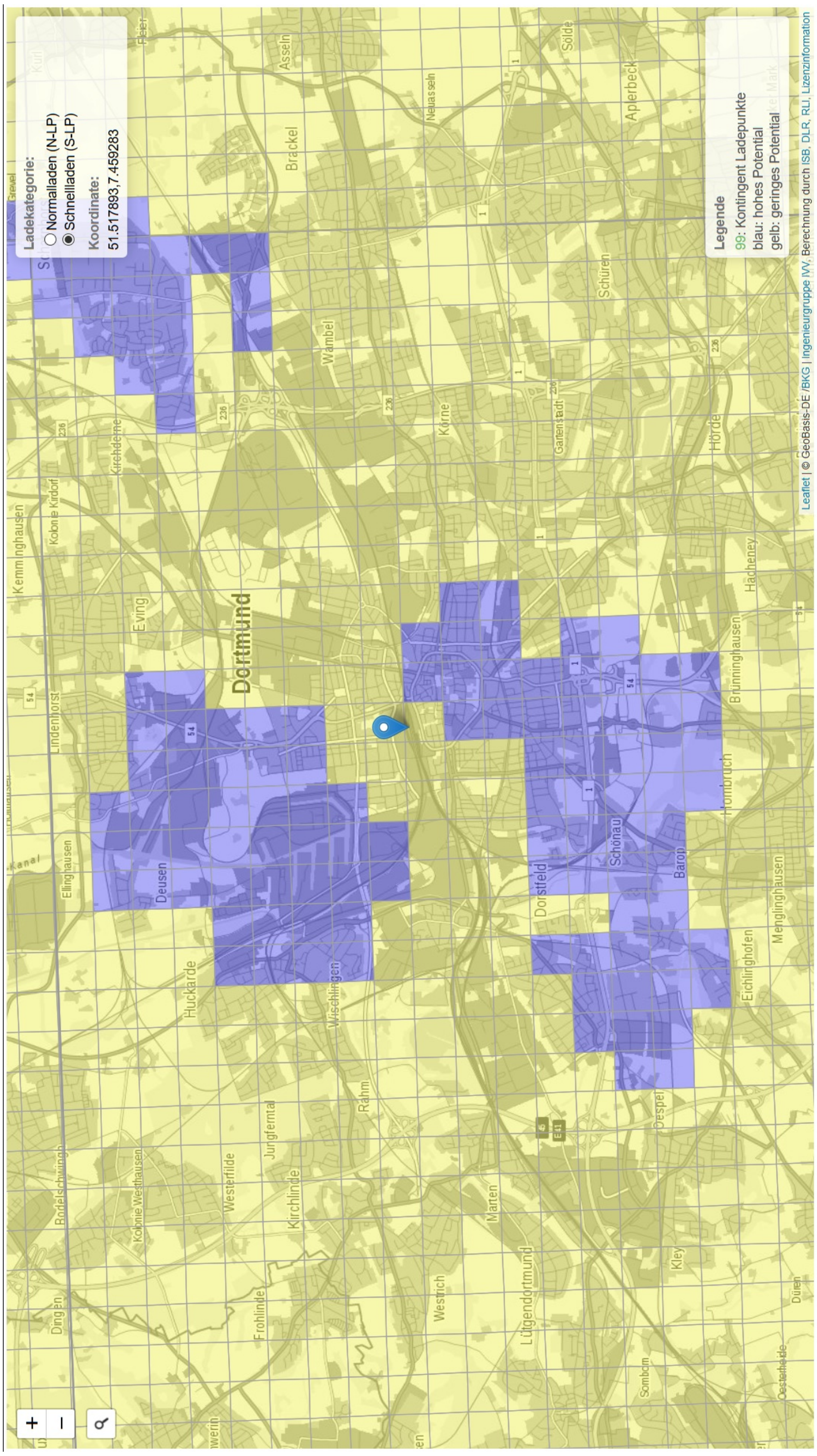



**Figure A.1:** Fastcharging map of Dortmund [59]

## A.2. Design basis for main cables

Graph A.2 shows the expected total peak power of a building depending on the number of apartments. Due to the simultaneity factor, it does not increase proportionally to the number of apartments.

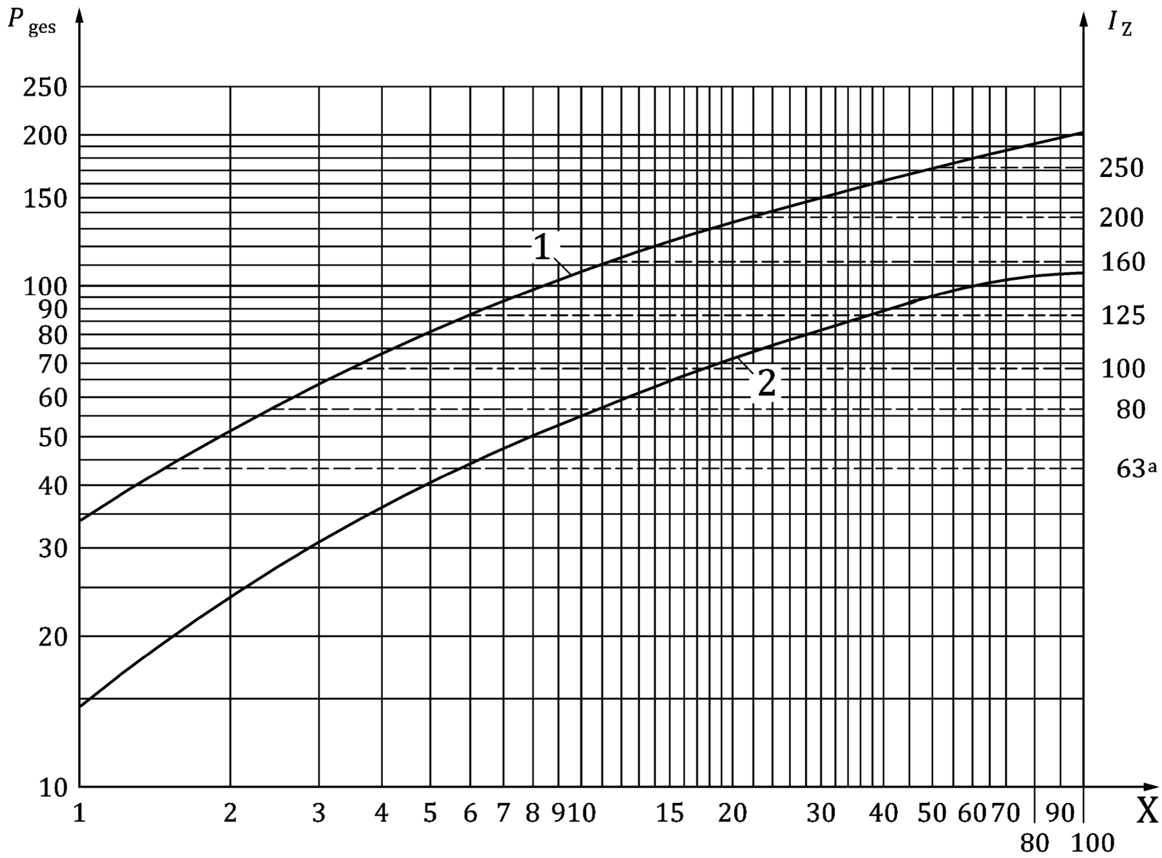



**Figure A.2:** Design basis for main cables [60]

| **Legend** | |
|---|---|
| 1 | With electric hot water preparation for bathing or showering purposes |
| 2 | Without electric hot water preparation for bathing or showering purposes |
| $I_z$ | Minimum required current carrying capacity, in A |
| | Numerical values = suitable rated currents of assigned overcurrent protection devices |
| $P_{ges}$ | Power resulting from the required current carrying capacity and the nominal voltage (assuming cos phi of 1), in kW |
| X | Number of apartments |
| a | Minimum protection to ensure selectivity of safety fuses |

## A.3. Power loss EV

Table A.1 shows how much energy was needed to fully charge the battery. Due to the fact that the amount of energy required exceeds the capacity of the battery, charging losses can be expected.

**Table A.1:** Charging loss - ADAC Ecotest 2018 [61]

| | Battery capacity [kWh] | Full charging (Ecotest) [kWh] | Used power [%] |
|---|---|---|---|
| Tesla Model X 100D | 100.0 | 108.3 | 92.3 |
| Tesla Model S P90D | 90.0 | 94.5 | 95.2 |
| Hyundai Kona Elektro Trend | 64.0 | 73.9 | 86.6 |
| Opel Ampera-e First Edition | 60.0 | 67.4 | 89.0 |
| Renault Zoe Intens | 41.0 | 49.5 | 82.8 |
| Hyundai Ioniq Elektro Style | 28.0 | 30.9 | 90.6 |
| Nissan Leaf II Acenta | 40.0 | 44.5 | 89.9 |
| BMW i3 (94 Ah) | 27.2 | 32.6 | 83.4 |
| Nissan e-NV 200 Evalia | 40.0 | 46.9 | 85.3 |
| Nissan Leaf I Acenta | 30.0 | 32.5 | 92.3 |
| Smart Fortwo Coupe EQ Prime | 17.6 | 20.5 | 85.9 |
| **Average:** | | | **88.5** |

## A.4. Consumption EV - ADAC Ecotest

Table A.2 shows consumption values of electric vehicles that have been measured using two different methods. It can be seen that the consumption values of the ADAC are far above the NEDC values.

**Table A.2:** Consumption - ADAC Ecotest [61]

| | Consumption ADAC Ecotest [kWh/100 km] | Consumption Manufacturer (NEDC) [kWh/100 km] |
|---|---|---|
| Hyundai Ioniq Elektro Style | 14.7 | 11.5 |
| VW e-Golf | 17.3 | 12.7 |
| BMW i3 | 17.4 | 12.6 |
| Smart Fortwo Coupe EQ Prime | 18.3 | 12.9 |
| Hyundai Kona Elektro Trend | 19.5 | 14.3 |
| Opel Ampera-e First Edition | 19.7 | 14.5 |
| Renault Zoe Intens | 20.3 | 13.3 |
| Nissan Leaf I Acenta | 20.5 | 15.0 |
| Nissan Leaf II Acenta | 22.1 | 15.2 |
| Tesla Model S P90D | 24.0 | 20.0 |
| Tesla Model X 100D | 24.0 | 20.8 |
| **Average:** | **19.8** | **14.8** |

## A.5. WLTP and NEDC test condition

Table A.3 shows the different test conditions of the WLTP and the NEDC procedure.

**Table A.3:** WLTP vs. NEDC [62]

| | Units | NEDC | WLTC |
|---|---|---|---|
| Start condition | | cold | cold |
| Duration | s | 1180.00 | 1800.00 |
| Distance | km | 11.03 | 23.27 |
| Mean velocity | km/h | 33.60 | 46.50 |
| Max. velocity | km/h | 120.00 | 131.30 |
| Stop phases | | 14.00 | 9.00 |
| **Durations:** | | | |
| - Stop | s | 280.00 | 226.00 |
| - Constant driving | s | 475.00 | 66.00 |
| - Acceleration | s | 247.00 | 789.00 |
| - Deceleration | s | 178.00 | 719.00 |
| **Shares:** | | | |
| - Stop | | 23.70% | 12.60% |
| - Constant driving | | 40.30% | 3.70% |
| - Acceleration | | 20.90% | 43.80% |
| - Deceleration | | 15.10% | 39.90% |
| Mean positive acceleration | $m/s^2$ | 0.59 | 0.41 |
| Max. positive acceleration | $m/s^2$ | 1.04 | 1.67 |
| Mean positive vel * acc (acceleration phases) | $m^2/s^3$ | 4.97 | 4.54 |
| Mean positive vel * acc (whole cycle) | $m^2/s^3$ | 1.04 | 1.99 |
| Max. positive vel * acc | $m^2/s^3$ | 9.22 | 21.01 |
| Mean deceleration | $m/s^2$ | -0.82 | -0.45 |
| Min. deceleration | $m/s^2$ | -1.39 | -1.50 |

## A.6. Costs of charging stations

Table A.3 shows the approximate cost of installing a DC charging point.

| | Level 2 Home | Level 2 Parking Garage | Level 2 Curb-side | DC Fast Charging | Description/Key Assumptions |
|---|---|---|---|---|---|
| Charge station hardware | $450–$1,000 | $1,500–$2,500 | $1,500–$3,000 | $12,000–$35,000 | |
| Electrician Materials | $50–$150 | $210–$510 | $150–$300 | $300–$600 | • $1.50–2.50/ft for conduit and wire, plus misc other materials<br>• $50–80/hour (per dist?)<br>• $500–1000 if new breaker is required<br>• Assume 2x electrical cost for level 3 |
| Electrician Labor | $100–$350 | $1,240–$2,940 | $800–$1,500 | $1,600–$3,000 | |
| Other Materials | | $50–$100 | $50–$150 | $100–$400 | • $25–100/ft for trenching/boring—depends on surface, soil, and underground complexity<br>• Mounting, signage, protection, and restoration also included here, but don't usually contribute more than a few hundred dollars |
| Other Labor | | $250–$750 | $2,500–$7,500 | $5,000–$15,000 | |
| Transformer | NA | NA | NA | $10,000–$25,000 | • 480V transformer installed by utility |
| Mobilization | $50–$200 | $250–$500 | $250–$500 | $600–$1,200 | • Home: 1–3 hours of electrician time for a home installation<br>• Public: $250–500 of time for 1–2 electricians and other labor. We found that the work could usually be completed in a single visit from each contractor. |
| Permitting | $0–$100 | $50–$200 | $50–$200 | $50–$200 | • Varies city to city, often a flat fee for one or several stations |

**Figure A.3:** Costs of DC charging point [63]

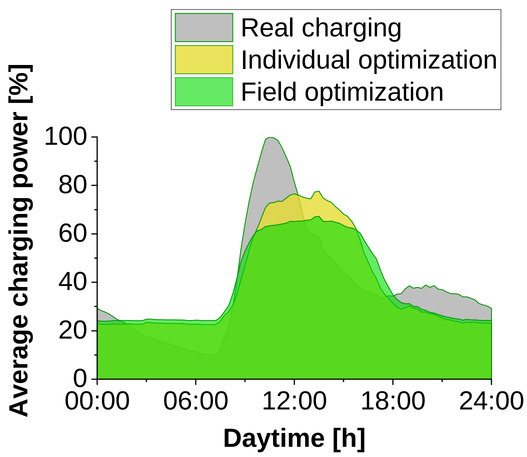
## A.7. Peak load reduction - all parking facilities

**Table A.4:** Peak load reduction - all parking facilities

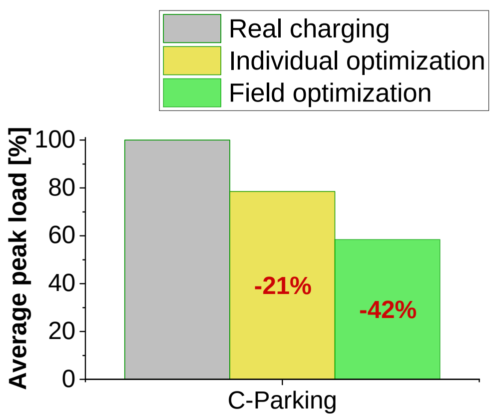
| | Category | Ø parking time | Optimization improvements | |
|---|---|---|---|---|
| | | | Individual | Field |
| **C Parking** | Public | 07:14 h | 21% | 42% |
| **E Parking** | Public | 05:31 h | 19% | 37% |
| **K Parking** | Public | 07:00 h | 19% | 35% |
| **R Parking** | Public | 01:44 h | 4% | 12% |
| **X Parking** | Public | 02:56 h | 9% | 24% |
| **H Parking** | Commercial | 06:14 h | 32% | 49% |
| **I Parking** | Commercial | 06:34 h | 39% | 55% |
| **S Parking** | Commercial | 05:52 h | 26% | 44% |
| **P Parking** | Residential | 11:13 h | 51% | 55% |

## A.8. Results - further parking facilities

### A.8.1. C-Parking



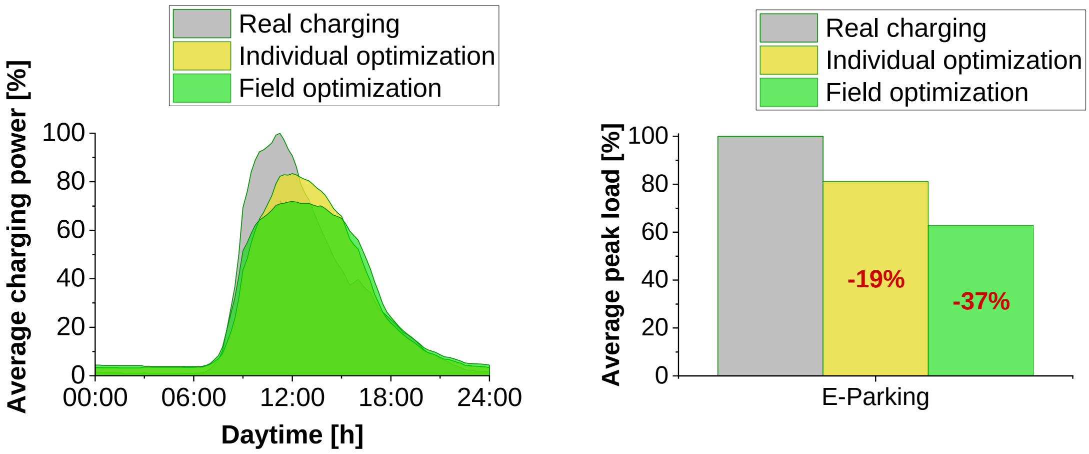

(a) Load profile




(b) Peak load reduction

**Figure A.4:** Optimizations - public charging - C-Parking

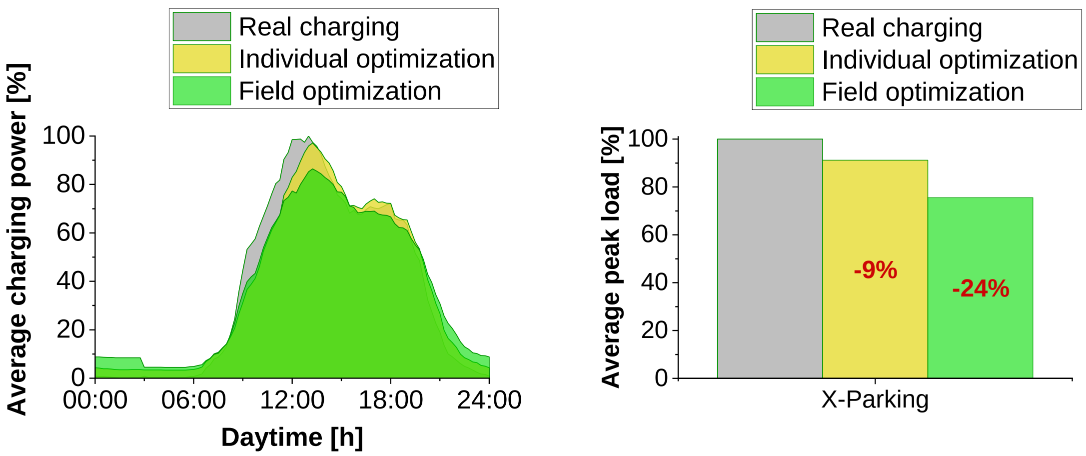
### A.8.2. E-Parking




(a) Load profile (b) Peak load reduction

**Figure A.5:** Optimizations - public charging - E-Parking

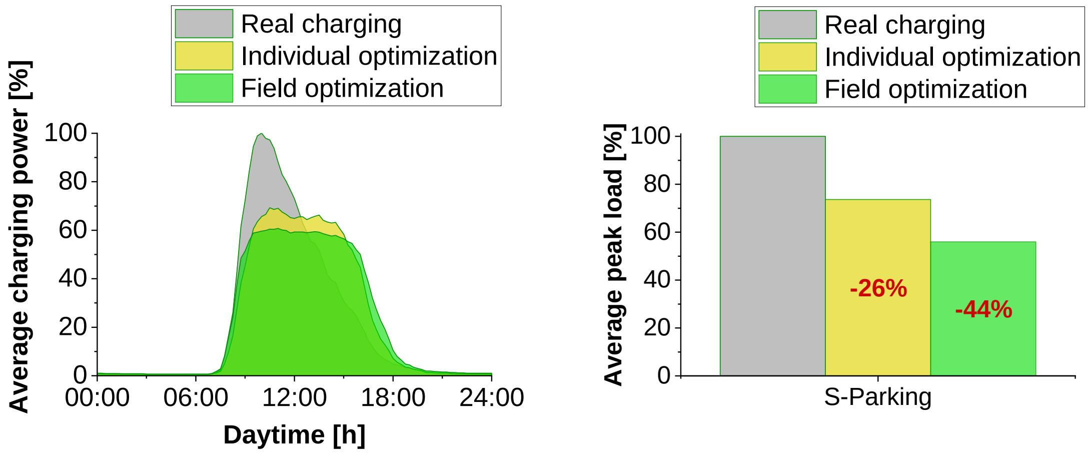
### A.8.3. X-Parking




(a) Load profile (b) Peak load reduction

**Figure A.6:** Optimizations - public charging - X-Parking

### A.8.4. S-Parking




(a) Load profile (b) Peak load reduction

**Figure A.7:** Optimizations - commercial charging - S-Parking

# References

[1] Z. Moghaddam, I. Ahmad, D. Habibi, and Q. V. Phung, “Smart charging strategy for electric vehicle charging stations,” *IEEE Transactions on Transportation Electrification*, vol. 4, no. 1, pp. 76–88, March 2018.

[2] X. Liang, “Emerging power quality challenges due to integration of renewable energy sources,” *IEEE Transactions on Industry Applications*, vol. 53, no. 2, pp. 855–866, March 2017.

[3] R. Rana and S. Mishra, “Day-ahead scheduling of electric vehicles for overloading management in active distribution system via web-based application,” *IEEE Systems Journal*, vol. 13, no. 3, pp. 3422–3432, Sep. 2019.

[4] B. für Wirtschaft und Energie, “Aktionsplan stromnetz,” Online, Aug. 2018. [Online]. Available: https://www.bmwi.de/Redaktion/DE/Downloads/A/aktionsplan-stromnetz.pdf?__blob=publicationFile&v=8

[5] B. für Verkehr und digitale Infrastruktur, “Der breitbandatlas,” Online, Oct. 2019. [Online]. Available: https://www.bmvi.de/DE/Themen/Digitales/Breitbandausbau/Breitbandatlas-Karte/start.html

[6] Z. Wei, Y. Li, Y. Zhang, and L. Cai, “Intelligent parking garage ev charging scheduling considering battery charging characteristic,” *IEEE Transactions on Industrial Electronics*, vol. 65, no. 3, pp. 2806–2816, March 2018.

[7] V. Torres-Sanz, J. A. Sanguesa, F. J. Martinez, P. Garrido, and J. M. Marquez-Barja, “Enhancing the charging process of electric vehicles at residential homes,” *IEEE Access*, vol. 6, pp. 22 875–22 888, 2018.

[8] L. Chen, C. Y. Chung, Y. Nie, and R. Yu, “Modeling and optimization of electric vehicle charging load in a parking lot,” in *2013 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, Dec 2013, pp. 1–5.

[9] Bundesministerium für Verkehr und digitale Infrastruktur, Bonn, “Mobilität

in Deutschland - Ergebnisbericht," 2018. [Online]. Available: http://www.mobilitaet-in-deutschland.de/pdf/MiD2017_Ergebnisbericht.pdf

[10] Braunschweiger Verkehrs-GmbH, "Braunschweig fährt jetzt induktiv!" 2014. [Online]. Available: https://www.verkehr-bs.de/fileadmin/user_upload/downloads/Emil/A5_emil_Flyer_WEB.pdf

[11] BMW AG, "Market launch for BMW Wireless Charging," May 2015. [Online]. Available: https://www.press.bmwgroup.com/global/article/attachment/T0281369EN/408765

[12] S. Jeong, Y. J. Jang, and D. Kum, "Economic analysis of the dynamic charging electric vehicle," *IEEE Transactions on Power Electronics*, vol. 30, no. 11, pp. 6368–6377, Nov 2015.

[13] J. "Eickelmann, *Wachstumsmotor Elektromobilitaet*. PHOENIX CONTACT Deutschland GmbH, 2017.

[14] J. "Klinger, *Ladeinfrastruktur fuer Elektromobilität im privaten und halboeffentlichen Bereich*. VDE Verlag, 2018.

[15] P. "Przemyslaw Komarnicki, J. Haubrock, and Z. Styczynski, *Elektromobilität und Sektorenkopplung Infrastruktur- und Systemkomponenten*. Springer-Verlag GmbH Deutschland, 2018.

[16] PHOENIX CONTACT Deutschland GmbH, "Lösungen für die Elektromobilität," 2013. [Online]. Available: https://www.phoenixcontact.com/assets/downloads_ed/global/web_dwl_promotion/Bro_E-Mobility_DE_low_final.pdf

[17] M. Weigelt, A. Mayr, R. Böhm, A. Kühl, and J. Franke, "Quo vehis, electromobility?" *ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb*, vol. 113, no. 1-2, pp. 59–63, Feb 2018. [Online]. Available: https://doi.org/10.3139/104.111863

[18] M. Alharbi, M. Dahidah, V. Pickert, and J. Yu, "Comparison of sic-based dc-dc

modular converters for ev fast dc chargers," in *2019 IEEE International Conference on Industrial Technology (ICIT)*, Feb 2019, pp. 1681–1688.

[19] T. G. GmbH, "Introducing v3 supercharging," Online, Mar. 2019. [Online]. Available: https://www.tesla.com/de_DE/blog/introducing-v3-supercharging

[20] Nationale Plattform Elektromobilitaet , "Fortschrittsbericht 2018 - Markthochlaufphase," May 2018. [Online]. Available: http://nationale-plattform-elektromobilitaet.de/fileadmin/user_upload/Redaktion/NPE_Fortschrittsbericht_2018_barrierefrei.pdf

[21] M. Lillebo, S. Zaferanlouei, A. Zecchino, and H. Farahmand, "Impact of large-scale ev integration and fast chargers in a norwegian lv grid," *The Journal of Engineering*, vol. 2019, no. 18, pp. 5104–5108, 2019.

[22] CDU, CSU und SPD, "Ein neuer Aufbruch für Europa - Eine neue Dynamik für Deutschland - Ein neuer Zusammenhalt für unser Land (coalition agreement 19th legislative period)," 2018. [Online]. Available: https://www.cdu.de/system/tdf/media/dokumente/koalitionsvertrag_2018.pdf?file=1

[23] Nationale Plattform Elektromobilität, "Ladeinfrastruktur für Elektrofahrzeuge in Deutschland Statusbericht und Handlungsempfehlungen," 2015. [Online]. Available: http://nationale-plattform-elektromobilitaet.de/fileadmin/user_upload/Redaktion/NPE_AG3_Statusbericht_LIS_2015_barr_bf.pdf

[24] Bundesverband der Energie- und Wasserwirtschaft e. V., "Rund 13.500 öffentliche Ladepunkte in Deutschland," 2018. [Online]. Available: https://www.bdew.de/presse/presseinformationen/rund-13500-oeffentliche-ladepunkte-deutschland/

[25] Bundesministeriums für Verkehr und digitale Infrastruktur, "Dritter Aufruf zur Antragseinreichung," 19.11.2018. [Online]. Available: https://www.bmvi.de/SharedDocs/DE/Anlage/G/dritter-aufruf-antragseinreichung-foerderrichtlinie-ladeinfrastruktur-e-fahrzeuge.pdf?__blob=publicationFile

[26] Bundesministerium für Verkehr und digitale Infrastruktur, "Förderrichtlinie Ladeinfrastruktur für Elektrofahrzeuge in Deutschland," 2017. [Online]. Available: https://www.bav.bund.de/SharedDocs/Downloads/DE/Foerderung_Ladeinfrastruktur/Foerderrichtlinie.pdf;jsessionid=DB183657E874853B39483B223D2A6B0E.live21303?__blob=publicationFile&v=1

[27] A. Rautiainen, S. Repo, P. Jarventausta, A. Mutanen, K. Vuorilehto, and K. Jalkanen, "Statistical charging load modeling of phevs in electricity distribution networks using national travel survey data," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 1650–1659, Dec 2012.

[28] Bundesministerium für Wirtschaft und Energie, "Rechtsgutachten zur Anwendbarkeit von § 3 Preisangabenverordnung (PAngV) auf Ladestrom für Elektromobile sowie zur Zulässigkeit und Vereinbarkeit verschiedener am Markt befindlicher Tarifmodelle für Ladestrom mit den Vorgaben der PAngV," Aug. 2018. [Online]. Available: https://www.bmwi.de/Redaktion/DE/Downloads/P-R/preisangabe-fuer-und-abrechnung-von-ladestrom-fuer-elektromobile-rechtsgutachten.pdf?__blob=publicationFile&v=10

[29] Physikalisch-Technische Bundesanstalt, "PTB und Bundesnetzagentur unterstützen durch gemeinsames Handeln den Rollout eichrechtkonformer Ladeinfrastruktur in Deutschland," Online, Jan. 2019. [Online]. Available: https://www.ptb.de/cms/de/ptb/fachabteilungen/abt2/aktuelleforschung2/forschungsnachrichten.html?tx_news_pi1%5Bnews%5D=9390&tx_news_pi1%5Bcontroller%5D=News&tx_news_pi1%5Baction%5D=detail&tx_news_pi1%5Bday%5D=31&tx_news_pi1%5Bmonth%5D=1&tx_news_pi1%5Byear%5D=2019&cHash=77d66beaf9f03e4b8f3ffaea4bbe876a

[30] B. Vaidya and H. T. Mouftah, "Deployment of secure ev charging system using open charge point protocol," in *2018 14th International Wireless Communications Mobile Computing Conference (IWCMC)*, June 2018, pp. 922–927.

[31] C. C. Chan, "The state of the art of electric, hybrid, and fuel cell vehicles," *Proceedings of the IEEE*, vol. 95, no. 4, pp. 704–718, 2007.

[32] R. Cowan and S. Hultén, “Escaping lock-in: the case of the electric vehicle,” *Technological forecasting and social change*, vol. 53, no. 1, pp. 61–79, 1996.

[33] A. Rautiainen, J. Markkula, S. Repo, A. Kulmala, P. Järventauta, and K. Vuorilehto, “Plug-in vehicle ancillary services for a distribution network,” in *2013 Eighth International Conference and Exhibition on Ecological Vehicles and Renewable Energies (EVER)*, March 2013, pp. 1–8.

[34] Dr. Dieter Zetsche, “Daimler 2017: Daimler und die Transformation der Automobilindustrie,” 29.03.2017. [Online]. Available: https://www.daimler.com/dokumente/investoren/hauptversammlung/daimler-ir-hv-redezetsche-2017.pdf

[35] ADAC e.V., “Autokatalog - Detail: smart forfour EQ,” 12.02.2019. [Online]. Available: https://www.adac.de/infotestrat/autodatenbank/wunschauto/detail.aspx?mid=288069

[36] ——, “Autokatalog - Detail: VW eGolf,” 12.02.2019. [Online]. Available: https://www.adac.de/infotestrat/autodatenbank/wunschauto/detail.aspx?mid=266575&bezeichnung=vw-e-golf

[37] Hyundai Motor Deutschland GmbH, “Der neue HyundaiKONA Elektro,” 12.02.2019. [Online]. Available: https://www.hyundai.de/CMSPages/GetFile.aspx?guid=25990a85-65a3-485f-a5e9-83e83398e897

[38] Opel Automobile GmbH, “Ampera-e,” 12.02.2019. [Online]. Available: https://www.opel.de/fahrzeuge/ampera-e/uebersicht.html

[39] ADAC e.V., “Autokatalog - Detail: Opel Ampera-E Plus,” 12.02.2019. [Online]. Available: https://www.adac.de/infotestrat/autodatenbank/wunschauto/detail.aspx?mid=287895&bezeichnung=opel-ampera-e-plus

[40] EV-database, “Tesla Model S 100D.” [Online]. Available: https://ev-database.org/car/1088/Tesla-Model-S-100D#charge-table

[41] Bundesregierung, “Nationaler Entwicklungsplan Elektromobilität der Bun-

desregierung," 2009. [Online]. Available: https://www.bmu.de/fileadmin/bmu-import/files/pdfs/allgemein/application/pdf/nep_09_bmu_bf.pdf

[42] Kraftfahrt-Bundesamt, "Bestandsbarometer Personenkraftwagen am 1. Januar 2019 nach ausgewaehlten Kraftstoffarten," 01.01.2019. [Online]. Available: https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/j%C3%A4hrlich/2019_b_barometer.html?nn=2084378

[43] Kraftfahrt Bundesamt, "Bestandsbarometer Personenkraftwagen am 1. Januar 2017 nach ausgewaehlten Kraftstoffarten," 01.01.2017. [Online]. Available: https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/j%C3%A4hrlich/2017/2017_b_barometer.html?nn=1873496

[44] Kraftfahrt-Bundesamt, "Der Fahrzeugbestand im Überblick am 1. Januar 2018," 19.03.2019. [Online]. Available: https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/j%C3%A4hrlich/2018/2018_b_ueberblick_pdf.pdf?__blob=publicationFile&v=1

[45] ——, "Der Fahrzeugbestand im Überblick am 1. Januar 2019," 19.03.2019. [Online]. Available: https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/j%C3%A4hrlich/2019_b_ueberblick_pdf.pdf?__blob=publicationFile&v=20

[46] Kraftfahrt Bundesamt, "Jahresbilanz der Neuzulassungen 2018," Online, 2019. [Online]. Available: https://www.kba.de/DE/Statistik/Fahrzeuge/Neuzulassungen/n_jahresbilanz.html?nn=644522

[47] Opplysningsradet for veitrafikken, "Januar juni 2019: Elbilens halvar," Online, Jul. 2019. [Online]. Available: https://ofv.no/aktuelt/2019/januar-juni-2019-elbilens-halv%C3%A5r-1

[48] C. Andrews, "Uk needs better charging [automotive charging infrastructure]," *Engineering Technology*, vol. 12, no. 2, pp. 62–63, March 2017.

[49] R. Mehta, D. Srinivasan, A. M. Khambadkone, J. Yang, and A. Trivedi, "Smart charging strategies for optimal integration of plug-in electric vehicles within

existing distribution system infrastructure," *IEEE Transactions on Smart Grid*, vol. 9, no. 1, pp. 299–312, Jan 2018.

[50] M. Gjelaj, C. Træholt, S. Hashemi, and P. B. Andersen, "Optimal design of dc fast-charging stations for evs in low voltage grids," in *2017 IEEE Transportation Electrification Conference and Expo (ITEC)*, June 2017, pp. 684–689.

[51] S. Bai and S. M. Lukic, "Unified active filter and energy storage system for an mw electric vehicle charging station," *IEEE Transactions on Power Electronics*, vol. 28, no. 12, pp. 5793–5803, Dec 2013.

[52] Kraftfahrt-Bundesamt, "CO2 emission and fuel consumption type test values of pas-senger vehicles with a maximum of nine seats and caravans (Category M1: passenger car, caravan)," Mar. 2019, 15. [Online]. Available: https://www.kba.de/SharedDocs/Publikationen/DE/Fahrzeugtechnik/SV/sv222_m1_kraft_pdf.pdf?__blob=publicationFile&v=25

[53] Volkswagen AG, "Der e-Golf," 2019. [Online]. Available: https://www.volkswagen.de/de/models/e-golf.html

[54] BMW AG, "BMW i3 - Auf einen Blick," 2019. [Online]. Available: https://www.bmw.de/de/neufahrzeuge/bmw-i/i3/2017/auf-einen-blick.html

[55] NISSAN Center Europe GmbH, "Der neue NISSAN LEAF," 2019. [Online]. Available: https://www.nissan.de/fahrzeuge/neuwagen/leaf/reichweite-aufladen.html

[56] G. Fontaras, B. Ciuffo, N. Zacharof, S. Tsiakmakis, A. Marotta, J. Pavlovic, and K. Anagnostopoulos, "The difference between reported and real-world co2 emissions: How much improvement can be expected by wltp introduction?" *Transportation Research Procedia*, vol. 25, pp. 3933–3943, 2017.

[57] J. Pavlovic, B. Ciuffo, G. Fontaras, V. Valverde, and A. Marotta, "How much difference in type-approval co2 emissions from passenger cars in europe can be expected from changing to the new test procedure (nedc vs. wltp)?" *Transportation Research Part A: Policy and Practice*, vol. 111, pp. 136–147, 2018.

[58] J. Rolink and C. Rehtanz, “Capacity of low voltage grids for electric vehicles,” in *2011 10th International Conference on Environment and Electrical Engineering*, May 2011, pp. 1–4.

[59] Bundesministeriums für Verkehr und digitale Infrastruktur, “Demand calculation tool for the location,” Mar. 2019. [Online]. Available: https://www.zdm-emob.de/Kartendarstellung/NLPuSLP.html

[60] *Electrical installations in residential buildings - Part 1: Planning principles*, German Institute for Standardization Std. DIN 18 015-1, 2018. [Online]. Available: https://www.perinorm.com/results.aspx#

[61] ADAC, “Elektroautos im Test: So hoch ist der Stromverbrauch,” Oct. 2018. [Online]. Available: https://www.adac.de/rund-ums-fahrzeug/tests/elektromobilitaet/stromverbrauch-elektroautos-adac-test/

[62] P. Mock, J. Kühlwein, U. Tietge, V. Franco, A. Bandivadekar, and J. German, “The WLTP: How a new test procedure for cars will affect fuel consumption values in the EU,” *International Council on Clean Transportation*, vol. 9, pp. 35–47, 2014.

[63] J. Agenbroad and B. Holland, “Pulling back the veil on ev charging station costs,” *Rocky Mountain Institute blog*, vol. 29, 2014.

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