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Bachelorarbeit

Integrate charging stations for electric vehicles on basis of specific scenarios

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Abstract

Electric mobility (e-mobility) and renewable energy, gets more and more an important factor for the future. As it stands, the federal government claim greenhouse gas neutrality not later than 2045. In reverse conclusion this means that in the transport sector the CO2 emission has to be decreased significantly, because of its being one of the biggest sectors of producing greenhouse gas by 18% in Germany. As a result the government expects 15 million electric vehicles (EV) on the streets till the end of 2030. The first projects done by Netze-BW investigated the efficiency of the actual grid by integrating several EV in different scenarios. They therefore applied various techniques, like intelligent charging management, central battery storage, and decentralized battery storage, which was directly integrated in the building. Furthermore, with the continuous development of electric cars, the infrastructure must also be examined in terms of charging stations. Many existing buildings or public charging stations were installed years ago based on the trend at the time. Since the market is booming in terms of EVs, a new concept must be considered here as well. The consideration here is now: I am constructing or planning a new building, for example a residential community of 30 apartments. How many charging points have to be installed here? How many charging points can the network handle without being overloaded? The goal should be to find the perfect number of charging points for an infrastructure to be developed. Several parameters have to be considered, such as the penetration of the grid, as well as the utilization by the users. As described above, there are currently already buildings that have installed charging points, but these are now insufficient as terms and development of EV progresses. It is now very difficult to charge one's electric car at work, for example, as there are simply no longer enough places to charge. The evaluation can be done, based on the data from the E-Mobility Carree. Here, 58 charging points for 45 electric cars were installed. From this, one can evaluate data such as: how many charging points were used at the same time during peak hours, for example in the evening hours? What was the penetration of the power grid here? On the basis of this, a model can be developed and evaluated that looks at this scenario in detail and can give an outlook as to what the necessary requirements for charging stations in new buildings or the expansion in existing buildings are.

Database:

- Inspection of group of people in the projects
- Efficiency of the grid
- Timestamps of loading processes
- Loaded energy per month
- Average count of loading processes

Regarding the point of existing infrastructures, it might be necessary to investigate how they can be upgraded. Here, a comparison can be made with new structures, and an expansion can be planned accordingly. In addition to the current state of EV, more technologies have been developed, such as vehicle to grid (V2G). The V2G technology could help to further relieve the grid. The idea now is that the EV are available as additional external battery storage. On the aspect that we have different types of people (e.g. employees, pensioner), and in conclusion we have different charging scenarios, we could at any time charge the EV even if the State Of Charge (SOC) isn't that low. Charge the EV when the line voltage is low, and release the energy in peaks of the grid like in the evening hours by using the V2G technology. The efficiency of the grid builds on the V2G technology. If the

current flow in the grid isn't used, we could store it temporarily in the EV and give it back if it's needed. The whole topic is worth mentioning, because regarding V2G technology, the EV must be connected to a charging station. This could influence the number of charging points to be deployed at a specific location.

Kurzfassung

Elektromobilität und erneuerbare Energien werden immer mehr zu einem wichtigen Faktor für die Zukunft. Die Bundesregierung fordert die Treibhausgasneutralität bis spätestens 2045. Im Umkehrschluss bedeutet dies, dass im Verkehrssektor der CO2-Ausstoß deutlich gesenkt werden muss, da er mit 18 Prozent einer der größten Treibhausgasproduzenten in Deutschland ist. Daher plant die Bundesregierung mit 15 Millionen Elektrofahrzeugen auf den Straßen bis Ende 2030. Erste Projekte welche von Netze-BW durchgeführt wurden, untersuchten die Effizienz des aktuellen Stromnetzes durch die Integration mehrerer Elektrofahrzeuge in verschiedenen Szenarien. Dabei kamen verschiedene Techniken zum Einsatz, wie intelligentes Lademanagement, zentrale Batteriespeicher und ein dezentraler Batteriespeicher welcher direkt im Wohnhaus der installierten Ladesäule integriert wurde.

Darüber hinaus muss mit der kontinuierlichen Entwicklung von Elektroautos auch die Infrastruktur in Bezug auf Ladestationen untersucht werden. Viele bestehende Gebäude oder öffentliche Ladestationen wurden vor Jahren aufgrund des damaligen Trends installiert. Da der Markt für Elektroautos boomt, muss auch hier ein neues Konzept in Betracht gezogen werden. Die Überlegung dabei ist jetzt: Ich baue oder plane ein neues Gebäude, z.B. eine Wohnanlage mit 30 Wohnungen. Wie viele Ladepunkte müssen hier installiert werden? Wie viele Ladepunkte kann das Netz verkraften, ohne überlastet zu werden? Das Ziel sollte es sein, die perfekte Anzahl von Ladepunkten für eine zu entwickelnde Infrastruktur zu finden. Dabei sind mehrere Dinge zu berücksichtigen, wie z.B. die Durchdringung des Netzes, sowie die Nutzung durch die Nutzer. Wie oben beschrieben, gibt es derzeit bereits Gebäude, in denen Ladepunkte installiert sind, doch diese reichen mit fortschreitender Zeit und Entwicklung des Elektroautos nicht mehr aus. Es ist inzwischen sehr schwierig, sein Elektroauto beispielsweise am Arbeitsplatz aufzuladen, da es einfach nicht mehr genügend Ladepunkte gibt. Die Bewertung kann anhand der Daten der Projekte wie dem E-Mobility Carree vorgenommen werden. Hier wurden 58 Ladepunkte für 45 Elektroautos installiert. Daraus lassen sich Daten auswerten wie: Wie viele Ladepunkte wurden in Spitzenzeiten, wie zum Beispiel in den Abendstunden, gleichzeitig genutzt? Wie hoch war hier die Durchdringung des Stromnetzes? Darauf aufbauend kann ein Modell entwickelt und ausgewertet werden, das dieses Szenario detailliert betrachtet und einen Ausblick geben kann, wie hoch der notwendige Bedarf an Ladestationen in Neubauten oder der Ausbau in bestehenden Gebäuden ist.

Datenbank:

- Überprüfung des Personenkreises in den Projekten
- Wirkungsgrad des Netzes
- Zeitstempel der Ladevorgänge
- Geladene Energie pro Monat
- Durchschnittliche Anzahl von Ladevorgängen

Im Hinblick auf die bestehenden Infrastrukturen sollte untersucht werden, wie diese aufgerüstet werden können. Hier kann ein Vergleich mit neuen Strukturen angestellt werden und ein Ausbau entsprechend geplant werden.

Neben dem aktuellen Stand der Elektroautos wurden weitere Technologien wie V2G entwickelt. Die V2G-Technologie könnte dazu beitragen, die Entlastung des Stromnetzes weiter voranzutreiben. Die Idee könnte hierbei sein, dass die Elektroautos als zusätzliche externe Batteriespeicher zur Verfügung stehen. Unter dem Aspekt, dass wir unterschiedliche Personengruppen haben (z.B. Angestellte, Rentner) und somit unterschiedliche Ladeszenarien, könnten wir das Elektroauto jederzeit laden, auch wenn der SOC nicht so niedrig ist. Das Elektroauto soll demnach geladen werden wenn die Netzspannung niedrig ist und in Spitzenzeiten der Aulastung wieder Energie freigeben. Dies geschieht unter Betrachtung der V2G Technologie, mit welcher die Netzauslastung geglättet werden kann. Wenn der Stromfluss im Netz nicht genutzt wird, können wir ihn im Elektroauto zwischenlagern und bei Bedarf wieder abgeben. Das ganze Thema ist erwähnenswert, denn bei der V2G-Technologie muss das Elektroauto an eine Ladestation angeschlossen werden. Das würde auch das Modell dementsprechend beeinflussen in der kalkulation der benötigten Ladesäulen.

Abbreviations

EV Electric vehicles

CP Charging point

V2G Vehicle-to-grid

SOC State Of Charge

kWh Kilowatt-hour

kW Kilowatt

AC Alternate current

DC Direct current

kV Kilovolt

Electric mobility E-mobility

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1 Introduction

1.1 Problem statement and current state of the art

Electric mobility and renewable energy have seen an exponential increase in the last years and an end of this development is not in sight. Hence it is no miracle, the slogan *The future drives electrically* appears more and more in public. One of the current defining issues in the world is advancing climate change [SCL21]. In order to achieve the goal, of reducing global warming, a drastic cut in the emission of greenhouse gases, especially carbon dioxide (CO2), is required. Currently around 20% of EU-wide emissions result from the transport sector, with the trend still rising [Age]. With a share of around 18%, the transport sector is one of the main sources of greenhouse gas emissions in Germany. Vehicles are set to be emission-free by 2035 [Pat15]. The target of the government reaching greenhouse gas neutrality by the year 2045 is one factor for the booming of electric vehicles [Bun21].

Since 2018, the global electric car population has grown steadily [Mic22]. Even then around 5.6 million electric cars were registered as seen in Figure 1.1. This also happened under the strong promotion of the state, giving EV acquirers a guaranteed bonus [Age]. In Germany, approximately 142,000 electric cars were registered this year. The interest of people in e-mobility could be won directly, since Germany is the second largest market after Norway. By 2030, there should be around ten million EVs on the roads in Germany as discussed in [Bunb]. This will now be further boosted by the phasing-out of the internal combustion engine by 2035 [Buna]. Hence, it is now not only necessary to cover the end consumer of an electric vehicle, but also to provide the necessary infrastructure. The charging of EVs results in new requirements for the power grid and challenges for the grid operators.

1.2 Aim of the thesis

Due to the rise of approved EV [IEA22a], the current infrastructure in context to EV and the grid has to be reviewed, as the vehicles need to be supplied with electricity. Most of the buildings and public charging points (CP) were adapted to the requirements in the past. This poses several challenges now, as there have to be deployed more charging stations at already existing buildings, such as new buildings [GFJ18]. As we deflect later in the thesis, another important point is that EV owners prefer to charge their vehicles at the building. As a result, residential infrastructure needs enough parking places, equipped with the right number of CP, to guarantee reliable driving with EVs [H S22]. Various factors now need to be considered and evaluated. The basic prerequisite for the switch to e-mobility - is a comprehensive and even more importantly, a reliable - infrastructure for electric cars. In order to be able to drive the electric car permanently, charging is required. In normal cases this is done by the classic charging stations. However, it is not possible to install an arbitrary number of charging columns at various locations, the environment must be analyzed in this regard as well. A major challenge is our power grid. The low-voltage grid, to which the charging stations are mostly connected, was not designed and intended for such consumers as several CP. The goal of this thesis is to determine the requirements for an existing or new infrastructure, and to derive a number of charging stations. How can I adapt a building that is already equipped with CPs to the rapid increase of electric cars [IEA22b]? It is now impossible to charge your electric car during working hours at certain public locations, as the ratio of electric cars and required CPs are into a huge imbalance. The same applies to new buildings. How many charging columns need to be installed? How many charging columns can the power grid withstand? What other limitations might there be? From an evaluation of various projects, a model will be developed which captures all of the necessary characteristics of an infrastructure in order to calculate the exact number of charging columns required for different ,objects.

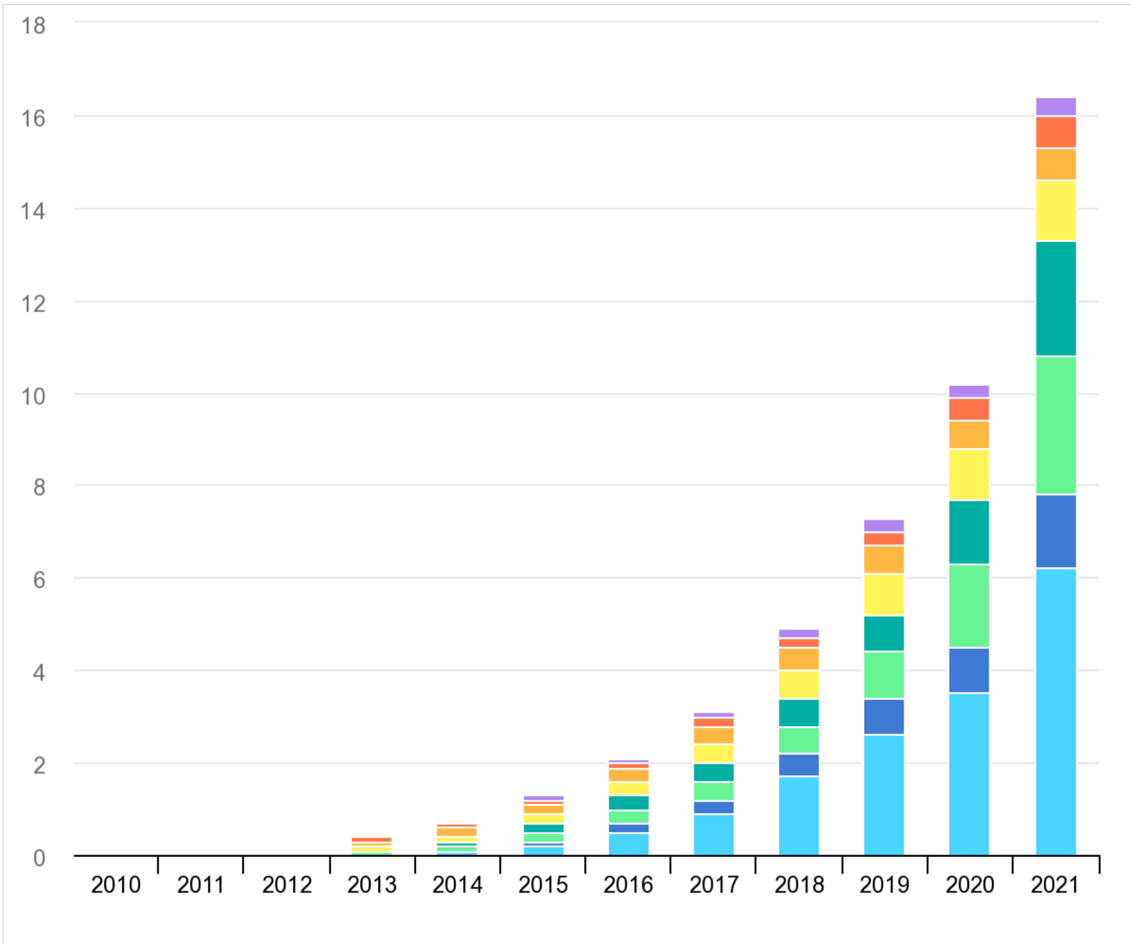

Figure 1.1: Global electric car stock for different markets in millions as captured by IEA [IEA22b]

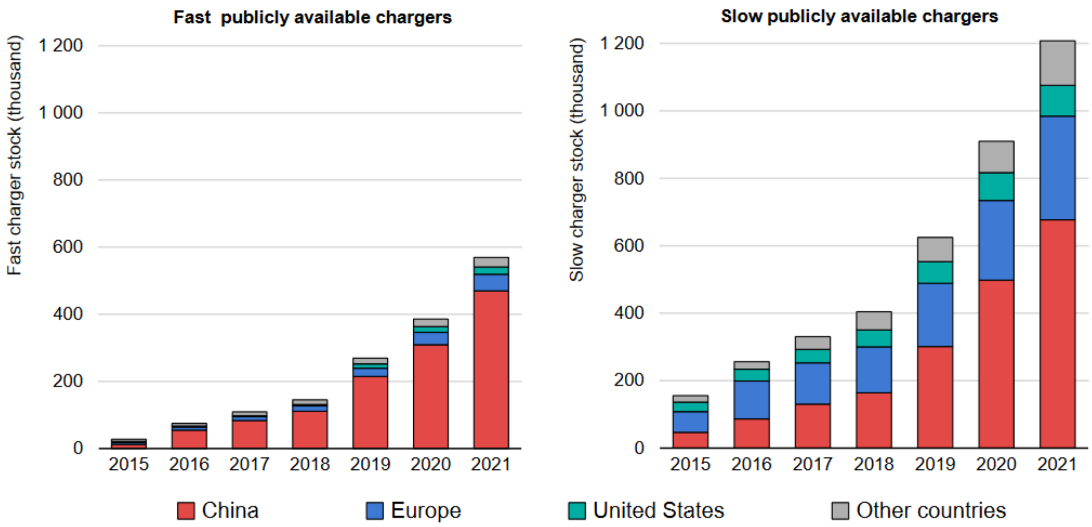

Figure 1.2: Global charger stock publicly accessible as captured by IEA [IEA22a]

Figure 1.1 and Figure 1.2 already show the lack of charging stations worldwide. It can be seen that there are significantly more EVs registered than there are charging stations. There is a huge imbalance in this relation, which is why there is an urgent need to adapt and expand the charging infrastructure, as also seen in [Ene22] and [ACE21]. However, it should be noted that private charging stations are not shown in the diagram. The current status in Germany is 15 EVs for one CP, and the goal of the European Union is 10 EVs per charger [IEA22a]. As the rapidly rising of sold EV per time, more chargers have to be deployed to reach their goals as mentioned above.

Because of limited and varied battery capacity, charge events can take place anytime. From this, it follows that EV owners have to charge their vehicle at work or during shopping, for example. As the ratio of electric cars to charging stations is currently imbalanced, many users are afraid of not reaching their target destination. This is then reflected in increased charging processes. This is called range anxiety. The driver cannot estimate if he/she can reach the target destination by the current SOC of the vehicle [PBC+20].

Research questions

The following research question is derived in the aspects and problems described above: **What is the perfect number of battery charging points for electric vehicles at different infrastructures?**

Sub-questions

Our main research question has to be divided into more sub-questions to be answered.

1. Which infrastructures do exist?
2. Which time does the EV arrive at a charging point?
3. What is the parking position factor for every scenario?
4. How many charging columns can the power grid withstand?
5. What other limitations might there be?

1.3 Assumptions

1. Only purely electric vehicles will be discussed. Other types, for example hybrid electric vehicles and plug-in hybrid electric vehicles, are not taken into account.
2. Acceptance of the users, especially when the power has to be throttled due to the intelligent charging management, which results in a longer charging time will not be discussed.
3. The economic aspect, as the costs of integration of recommended charging points, is not modeled.

1.4 Methodology

Figure 1.3 shows a simplified illustration of the model to be developed to solve our problem formulation. First of all, we have to identify which factors are relevant to understand how the calculation should run. In Chapter 3, three different projects were analysed to determine representative elements. In addition, multiple methodologies and optimization techniques were presented, that influence the chosen parameters. It is not possible to connect as many EVs at CPs, this causes peaks in the grid which it cannot handle. Hence, it is essential to discuss the interconnection between parameters for our model and techniques to relieve the grid respectively to understand why some parameters could be chosen due to these techniques.

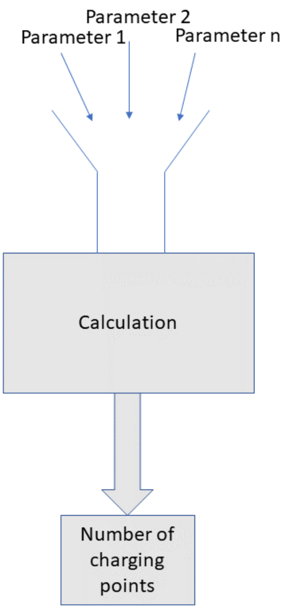

Figure 1.3: Simplified illustration of the model to be developed

Figure 1.3 gets updated later, as seen in Figure 4.1 and describes why elements were chosen for our model. In Chapter 4, the detailed model is described. Out of our captured data in Chapter 3, we derive our algorithm.

1.5 Thesis overview and chapters

The remainder of this work is structured as follows:

Altogether, the thesis is divided into six chapters, which are now presented and described more into detail.

Chapter 1 Introduction

The first chapter gives a general introduction to the content of the thesis and the current problems which developed around the topic, as well as our research question and sub-questions.

Chapter 2 Technical background

Chapter 2 introduces the technical background, which is necessary to classify the whole topic. What regulations are given and what difficulties arise in the implementation?

Chapter 3 Related work

Chapter 3 presents the necessary literature for the elaboration of the topic. Various pilot projects of Netze-BW are discussed and their results evaluated. Based on this and further literature, a model for the implementation of our research question will be developed in the following chapter.

Chapter 4 Design

In this chapter, the captured data from the literature research and the projects are projected onto the model to be developed. This is done by deriving technically recorded data and diagrams.

Chapter 5 Discussion

Discusses the results on diverse levels and shows how the model fits in the real world.

Chapter 6 Conclusion

Concludes our work and suggests future research.

2 Technical background

In this chapter, the relevant technical backgrounds and requirements should be displayed to understand the complexity behind the thesis. The ideal situation would be to install as many charging stations as desired at any location. However, there are a number of regulations that should now be discussed. The basic prerequisite for switching to e-mobility is a reliable and comprehensive infrastructure for electric cars. If the number of EVs increases as rapidly as described in Chapter 1, this will result in new demands on the power grid. The charging of electric cars will push the local power grid to its limits, those are even being exceeded already. When the power grid was designed years ago, before the idea of electric cars driving on the roads, the existing needs of the charging infrastructure was not taken into account. This has a direct impact on the core question of this work. To what extent is it possible to integrate charging stations intelligently without overloading the grid? What happens when a whole street switches to electric cars and they all charge via the same power cable?

2.1 How does the power grid work?

For a better illustration, we will now refer to the following diagram, which depicts the electricity grid.

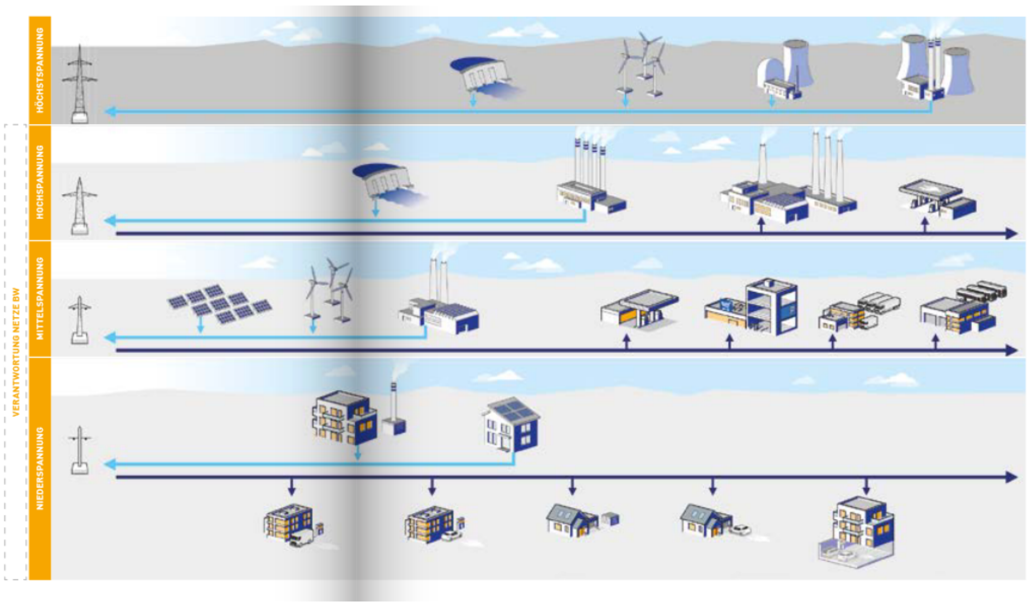

Figure 2.1: Structure of electricity grid [Net21a]

Overall, the electricity grid is divided into four different levels. But which of these levels should be considered when it comes to EVs and CPs? Generally speaking, the required or requested power describes the voltage level of the electricity grid. For a better understanding, it is necessary to examine charging facilities in the private and public sector. Private charging facilities, such as those in residential buildings, are connected to the low-voltage grid as normal. However, if there are larger public facilities, such as charging parks, these are connected directly to the medium-voltage grid due to the large load. With the ongoing development of electric trucks, such as the E-Actros from Mercedes, a connection to the high-voltage grid can also be discussed.

The state's proclaimed goal is to implement around one million charging options in the public sector by 2030. In the private sector the number should be even higher, due to charging preferences from EV owners tending to charge their vehicle at home. Conversely, this means that e-mobility needs strong electricity grids. Around 85% of charging processes take place in the private sector, this is why we take a closer look inside such scenarios than into the public sector. However, the low-voltage grid was not designed for such loads at the time. The power requirements of an EV far exceed those of a normal household. This is also illustrated in Figure 2.3

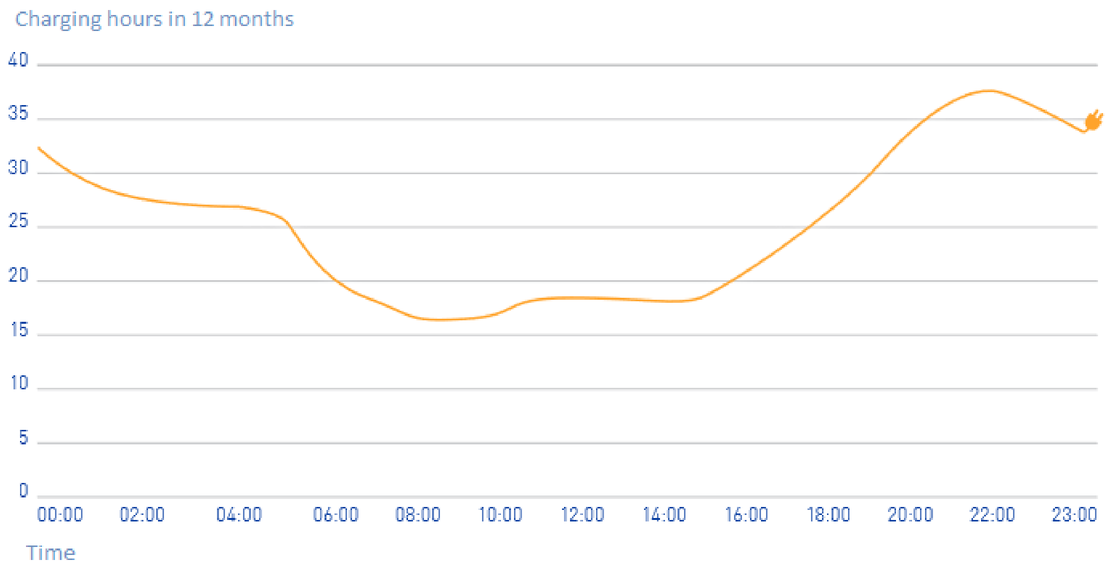

Figure 2.2: Moment of EV charging at the charging point [Net19a]

In Figure 2.2 we see the charging hours from EVs [Net19a] summarized over the project period (one year) at a specific time of the day. The participants preference is clearly to charge their EV in the evening hours, beginning at 19:00 h with its peak at 22:00 h and ending at 01:00 h. In examining this connection, it is important to capture the time events an EV arrives at a CP to understand the link between charging and utilization of the grid. Figure 2.3 shows the charging profile of a single EV between 22:00 h and 01:00 h. The charging profile of a single EV exceed a single household profile by a multiple. If we now consider that the low-voltage grid was only dimensioned for normal household profiles, big challenges arise with the integration of EV. Therefore, in case of development, important requirements are new technologies to have a smooth integration of the strong rising utilisation of EVs. These technologies will be displayed and discussed in Chapter 3.

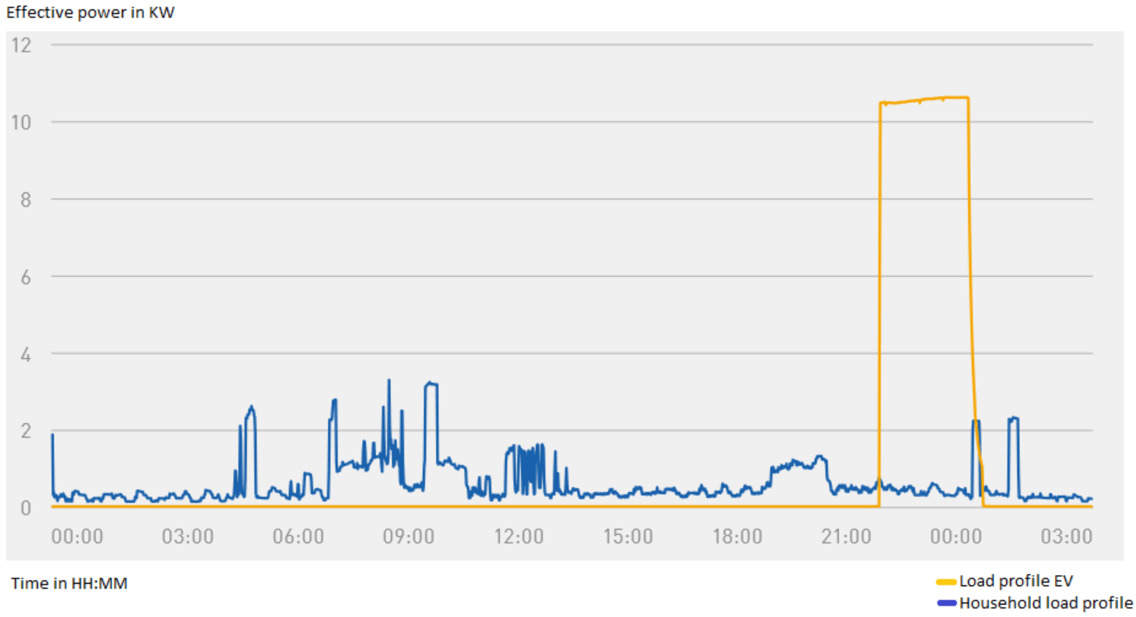

Figure 2.3: Load profile in a single-family house with and without an EV [Net19a]

Figure 2.3 shows, that the power demand of an EV can lead the power grid to critical load peaks. To prevent this, and to adequately dimension the power grids according to the power demand of several EV, the number of simultaneously charged EV is an important parameter. This requires grid reinforcements when expanding the charging infrastructure. Another important piece of information that can be taken from the load profile is the time at which an electric car is charged. This factor must be considered as well as the load on the grid itself.

2.2 Other restrictions

- Various charging needs of different EVs induces phase asymmetry.
- Differentiation of CP, for example fast or slow chargers.
- Type of environment.
- Difference between new and old buildings.

However, getting all of these EVs on the road quickly will require efforts such as regulatory frameworks, additional investment and development of new technologies.

In general, a distinction must also be made between two types of charging:

- Private
- Public

These two types will be discussed briefly in the following:

(a) Private: Not a publicly accessible space, for example home or workplace. Common examples are wall boxes with 11kW and 22kW charging power. These we will see in the projects evaluated.

(b) Public: Occasionally charging, for example shopping or fast charging during long distance trips on the highway. Common examples are wall boxes with 350kW charging power.

The big difference between private and public charging is the charging power. In public charging, more power usually has to be made available to the EV, as the times at the charging point are, or has to be, much shorter than they are in the private sector. The factor of charging time is also dependent on the phasing (one phase, two phase, three phase) of the car. The average time of EVs is briefly shown in the itemization underneath.

- Standard charging, 8-12 hours
- Normal charging, 6-8 hours
- Fast charging, 1-2 hours

Location	Type
Public	Car park
Public	Charging hub
Private	One-family house
Private	Multi-family house
Private industry sector	Company parking area

Table 2.1: Use cases of charging infrastructure at different locations

The supply of EVs can only be guaranteed with a strong power grid. We first have to discuss the construction of the electricity grid to understand the integration needs of charging infrastructure.

There are a total of four voltage levels in the electricity grid, which will be described

- Maximum voltage, 380kV and 220kV
- High voltage, 110kV
- Medium voltage, 30kV or 20kV or 10kV
- Low voltage, 230V or 400V

The connection of the charging infrastructure can therefore be carried out at several levels. Private facilities are connected directly to the low-voltage grid. Public and commercial charging parks with high cumulative power are supplied from medium voltage. Regarding the future, charging parks can also be connected to the high-voltage grid, for example electric vehicles with particularly high charging capacities.

2.3 Types of charging points

Three different types of charging have been discussed in [H S22]. An important note is how much performance a wall box provides. Different appropriation of energy produces a higher or lower workload of the grid. As we discuss later in Chapter 3, [Net19b], [Net21b] and [Net21c], different EV with different charging characteristics, as shown in the following enumeration, were chosen.

- Battery capacity
- Charging time
- Charging capacity
- Charging behaviour
- Range with 100% SoC

We have a variety of needs to address as we explore the different challenges presented by EVs.

Chapter 3 continues with more technical background in connection with our related work presented. An even better insight is given into the topic, as well as possibilities to implement charging infrastructure.

3 Related work

In this chapter, related work which is relevant for our model is presented and discussed. How does the charging behaviour of EV owners affect the electricity grid? Which technical solutions can be integrated in the infrastructure to maximize the number of EV in the electricity grid on one hand and relieve it on the other hand. Several projects by Netze-BW have taken place in the past. These will discussed and evaluated in this section and the captured data will be integrated into the model to be developed in Chapter 4. In the evaluation of these projects, our focus should be primarily on important elements which are necessary to bring our model to completion. Those are highlighted textually and exact data is provided in Chapter 4.
Attention should also be given to used techniques in the expansion of charging infrastructure, which help to integrate CP easier under current conditions. These techniques will influence the load factor of the grid, which will modify our outcome of CP calculated for an infrastructure.

Before evaluating the field tests, it is important to filter out factors which could be important irrespective of setting up a charging infrastructure. These should be displayed and discussed in the following section.

Important for the design of the model is the recording of different lifestyles and driving habits of people.

- Frequent driver
- Occasional driver
- Age groups (pensioners, families with kids)
- Driving behaviour
- Driving habits
- Previous experiences with EVs

3.1 Integration of an entire street in the grid

In this scenario [Net19a] and [Net19b], ten CPs are installed, one for each domestic home. As a result, an amount of consumers could access the grid in a very short time. What happens if a whole street switches to electric cars and they all charge via the same power cable?

Chosen environment:
A typical residential area, which is common in agglomerations, is where Netze BW [Net19b] supposes most of the EVs initially drives. Another key fact is that every resident is connected to the same electric circuit. As a result, the impact of simultaneous charging of EV to the grid can be reviewed.

In the following, the methods used to support or relieve the electricity grid will always be presented first.

Methodology for the charging process/ support of the electricity grid through

- Decentralized battery storage
- Centralized battery storage
- Intelligent charging management

During simultaneous charging of multiple EVs, high load peaks in the electricity grid appear as seen in Figure 3.1. In correlation to load peaks is the potential difference which occurs as an effect. This means the EV doesn't receive enough tension, and therefore charges with reduced demand. The particular potential difference is dependent to each individual wire cross section. The first conclusion is, if we build new infrastructures, the right dimensioned wire cross section can be selected early to challenge the respective requirements.

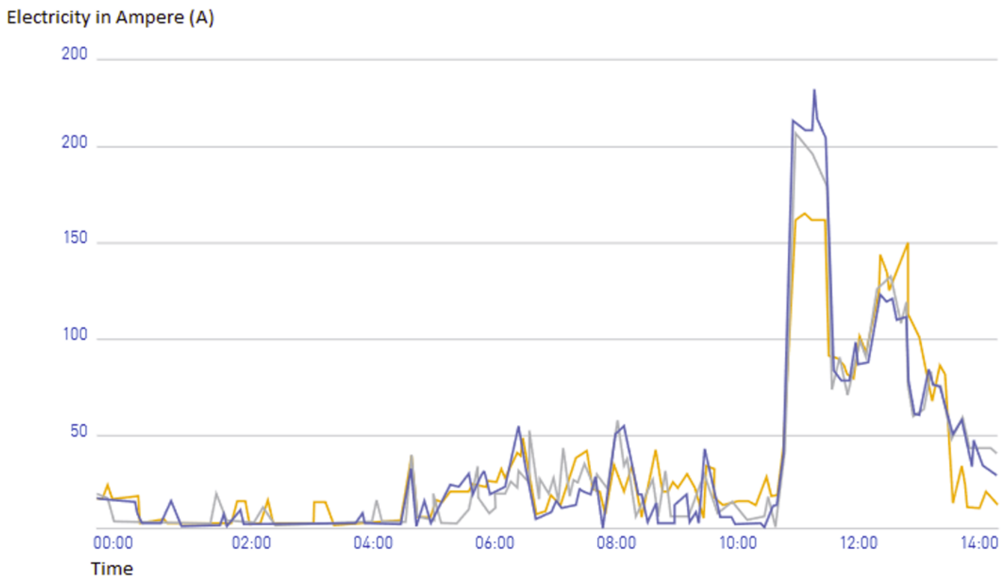

Figure 3.1: Stress test of power cable with ten EV charging simultaneously [Net19a]

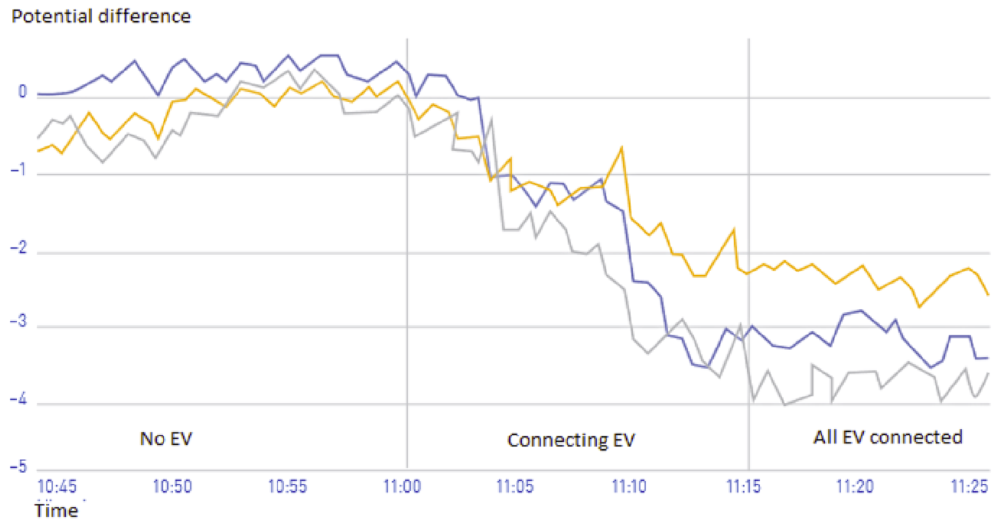

Figure 3.2: Stress test of power cable with ten EV charging simultaneously showing the resulting voltage drop [Net19a]

In connection to charging EVs, we influence the voltage in the grid as well. Every consumer used in the electric circuit has an impact on voltage quality. Therefore, it is important to capture voltage characteristics at an early stage. Figure 3.2 shows a voltage drop of 4% with ten EVs charged simultaneously. We see a clear change of voltage in our grid triggered by charging. Though, this potential difference in the limits doesn't need to be considered. A voltage drop is equal to EVs charging way slower, which results in a longer charging process.

Those high load peaks seen in Figure 3.1 can be prevented by external battery storage or intelligent charging management. The two methods presented above are solutions, which can be implemented quickly to relieve the grid. The intelligent charging management system avoids load peak in the grid by optimizing charging processes.

In the following, some of the functionalities are displayed to gain a better understanding of how those techniques work and how they could be used.

A distinction is made between:

- Preventative charging management: Charging points receive fixed schedules for maximum available charging power.
- Reactive charging management: Allows charging processes to be monitored and controlled in real time.

The schedules are created on the basis of empirical values and forecasts and take into account when the network is expected to be heavily utilized. Subdivision into release groups and release quotas:

- Release group: Depending on the time of day, charge with minimum or maximum power.
- Release quota: All customers can charge with the same power.

As the name suggests, reactive charging management allows charging processes to be monitored and controlled in real time. If we have a load peak in the grid, the charging power of implemented charging stations can be throttled, thus the grid gets relieved. However, each participant is guaranteed a minimum power of 5 kW. A minimum of 5 kW is required, as the car can then no longer be charged on its own. Then it requires unplugging and plugging into the charging adapter. If the bottleneck in the grid can be overcome, charging power is released again for each individual charging point.

Another possibility, alongside the intelligent charging management, is a decentralised battery storage system. This will be integrated at the same time the CP is integrated in the domestic home. It stores energy during the mid-day hours and releases it again in the evening.

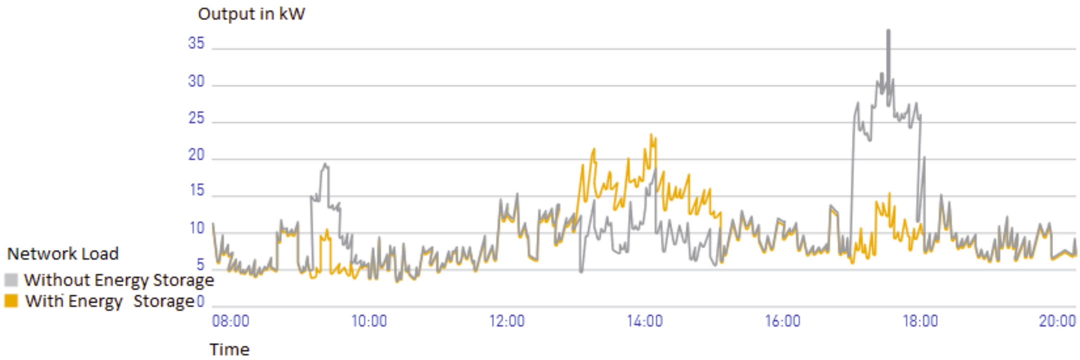

Figure 3.3: Network load with and without additional decentralised energy storage [Net19a]

What directly attracts attention in Figure 3.3 is that the network load with the energy storage is 20 kW less than without the additional energy storage. The only difference is the network stressing in mid-day hours while the battery storage is charged, without affecting the grid in a negative manner. The energy storage proves it is a good alternative to smooth the network load. The only disadvantage is that the decentralised energy storage only supplies a single EV.

Another possibility is to integrate centralized battery storage, directly connected to the low voltage system. The advantage and big difference in this case is that we cover the supply of every EV connected to the same electric circuit, in contrast to the decentralized energy storage. Due to high workload and rapid increase of voltage in the grid, the energy storage discharges itself to absorb the potential difference. This scenario is seen in Figure 3.3 at 17:00 h. The network load smoothed from about 35 kW into peak to only 15 kW. The other way around, the battery storage charges if the line voltage is normal. This is visible between 13:00 h and 15:00 h, where the output increases between 5 kW to 10 kW.

As seen in Figure 3.2, the charging of ten EVs results in a workload of nearly 100 kW and smoothed down with support of the battery storage to nearly 60 kW. Hence, this technical support should be discussed if we have enough space to install it.

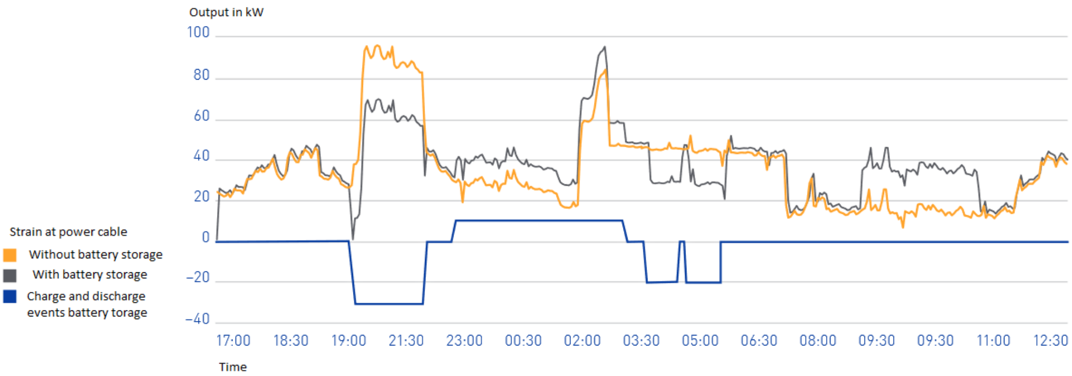

Figure 3.4: Stress test of power cable with and without a centralized battery storage [Net19a]

In Figure 3.4 we see into contrast to Figure 3.3 with the charge and discharge events of the battery storage. In both cases, we have a rapid increase of output in the evening hours. During this increase, the battery storage capacity decreases and smooths the output from nearly 100 kW to under 70 kW. The biggest advantage of the centralized storage is supplying multiple EV instead of a single one, and not only reacting to EVs, but also to other big electrical consumers accessing energy.

3.2 Integration of an underground car park in a big housing complex

Currently, about 53% of the residential units in Germany live in apartment buildings. This means that there is generally a high density of potential EVs in one location. Is it possible to set-up a charging park for such a scenario? This was analysed in [Net21b] [Net21a].

Chosen environment:
The chosen environment is a big apartment building, the big difference to [Net19b] is the higher number of residents per space. As a result, we have a higher density of potential EVs, as well charging infrastructure, as CPs are necessary in such scenarios. Altogether, 58 CP are installed within the framework of this project.

Methodology for the charging process/ support of the electricity grid through:

- Centralized charging management
- Two battery storages with a capacity of 18 kW and 19 kW
- Transfer of a separate power supply

In the E-Carree [Net21b], the intelligent charging management throttles the available charging power in the network connection point from 124 kW to 40 kW step by step as seen later in Figure 3.5. If several EVs are charged simultaneously, the intelligent charging management reduces the charging power of each CP downwards.

Tasks of charging management:

- Maximum available power is optimally distributed.

- Load peaks in the electricity grid are avoided.

Depending on the number of CPs, different scenarios can be considered that are presented below.

Installation of few charging points:
These can be supplied via the building's existing mains connection. This can be recorded via a measurement of the current load on the grid. If there is still enough capacity left in the power supply cable respectively in the electric circuit, the implementation could be done without a charging management system. The further upgrading of charging points can then be implemented with the help of a charging management system.

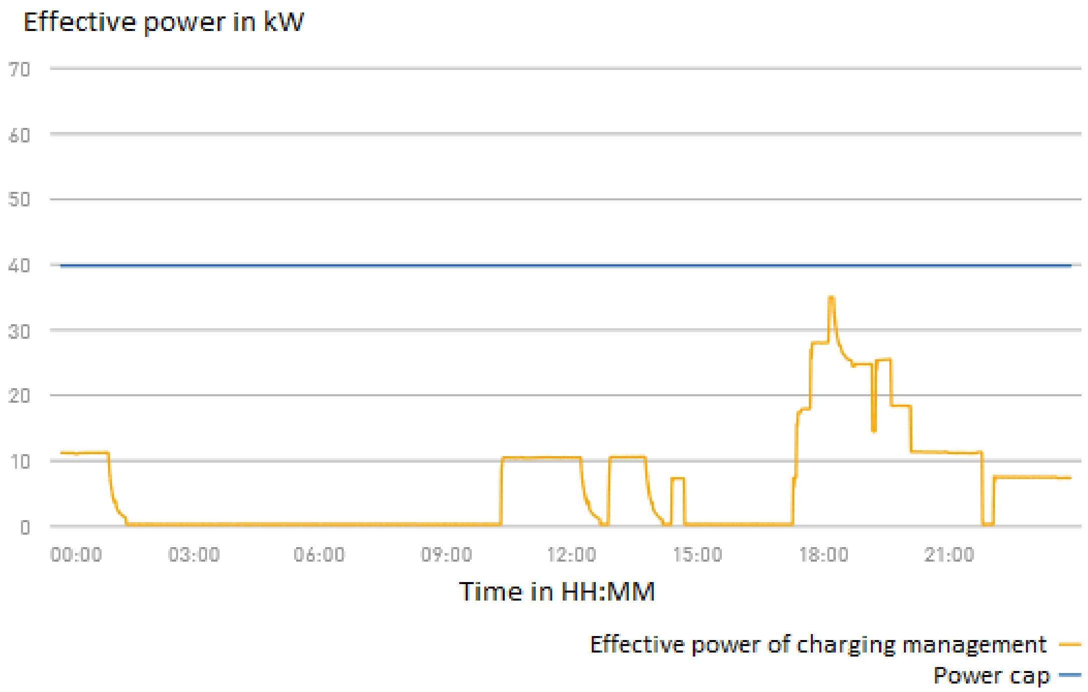

Figure 3.5: Charging management with reduced performance, charging four EV simultaneously [Net21a]

As per the description above, the effective power was throttled down by the charging management to 40 kW, shown by the blue line. What is striking is that four EV charging simultaneously don't even reach the power cap. Furthermore, we see a peak in the evening hours. What would be interesting would be the scenario of connecting one or two EVs in the system. The cap of 40 kW would be exceeded, then the charging management would throttle every CP in the circuit, which would result in less performance and therefore longer charging times. Figure 3.5 shows that the limitation of electricity demand in this case has no impact on the charging process of EVs.

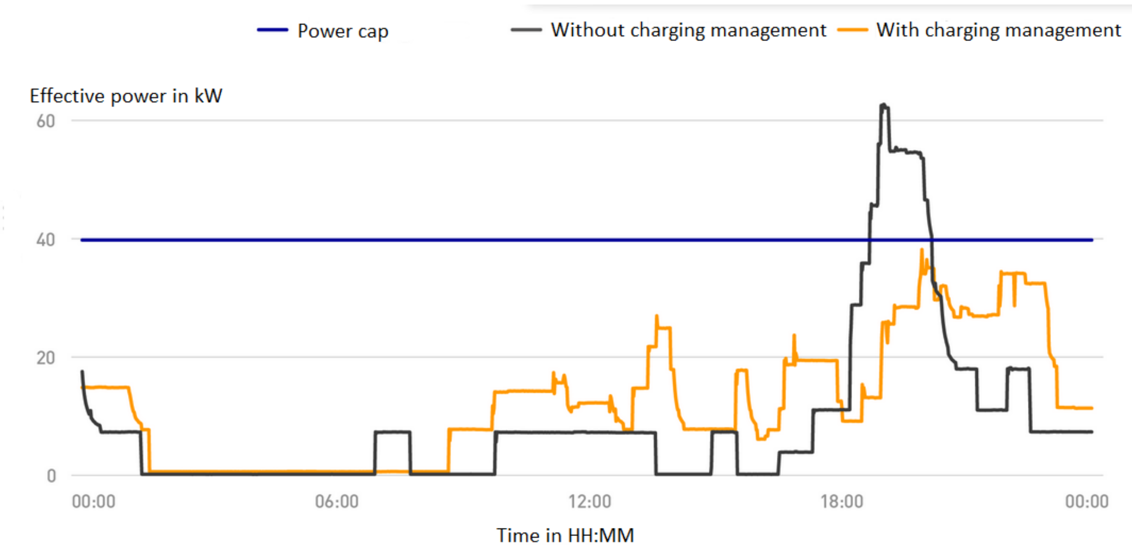

Figure 3.6: Charging management to relieve supply cable [Net21a]

In Figure 3.6, it can be seen that most charging takes place in the evening hours. This can be seen in the active power around 18:00 h. With the help of the charging management, there are no more load peaks in the grid, and the power limit is not exceeded.

Furthermore, a measuring unit and control unit will be installed directly at the grid connection point to detect load peaks at the grid connection point. Two operating modes are being investigated here.

- Static mode
- Dynamic mode

In dynamic mode, the battery storage provides additional power when a predefined limit value is exceeded in order to counteract a rise in the load curve. If the value falls below the limit, the battery storage recharges. In the test setup, however, this storage does not achieve the desired effect. Either it is not needed at all some days, or it is so overloaded that the storage unit cannot support the load peak. This means that the reference power at the grid connection point increases rapidly.

What is being addressed here for the very first time is the determination of parking spaces (parking spots/accommodation units). The so-called parking space factor represents how many parking spaces a resident can use. A factor of one would mean that each resident is guaranteed exactly one parking space. In relative terms, this is less than one. This means that not every resident has a guaranteed parking space. In our case not every resident will be guaranteed a CP. At first glance, this may not seem all that interesting. But it is, considering the increase in power and the utilisation of the electricity grid. The following abstract example is intended to illustrate this: We have 100 residential units in an apartment building. Each unit has one parking space. This results in a parking space factor of 1. If all parking spaces are electrified with a charging power of 11 kW, this results in a power increase of 100*11kW=1100kW. If there is only one parking space for every second residential unit, this means a parking space factor of 0.5. Then, we would have a power increase of 50*11kW=550kW. This shows that this factor must be taken into account to calculate the growth of electricity demand.

Charging behaviour of the participants:
Figure 3.7 shows us simultaneous charging events from the participants, captured over the project period in specified time segments. This figure will not be discussed in detail, for example how many EVs are charged in a period of the day, but a significant element is captured out of this graph. In the E-Allee, most of the participants charge their vehicle in the evening hours. Therefore, it is vital to capture charging preferences. For example, in this case we have a trend of charging process being equal on weekends or weekdays in the evening hours.

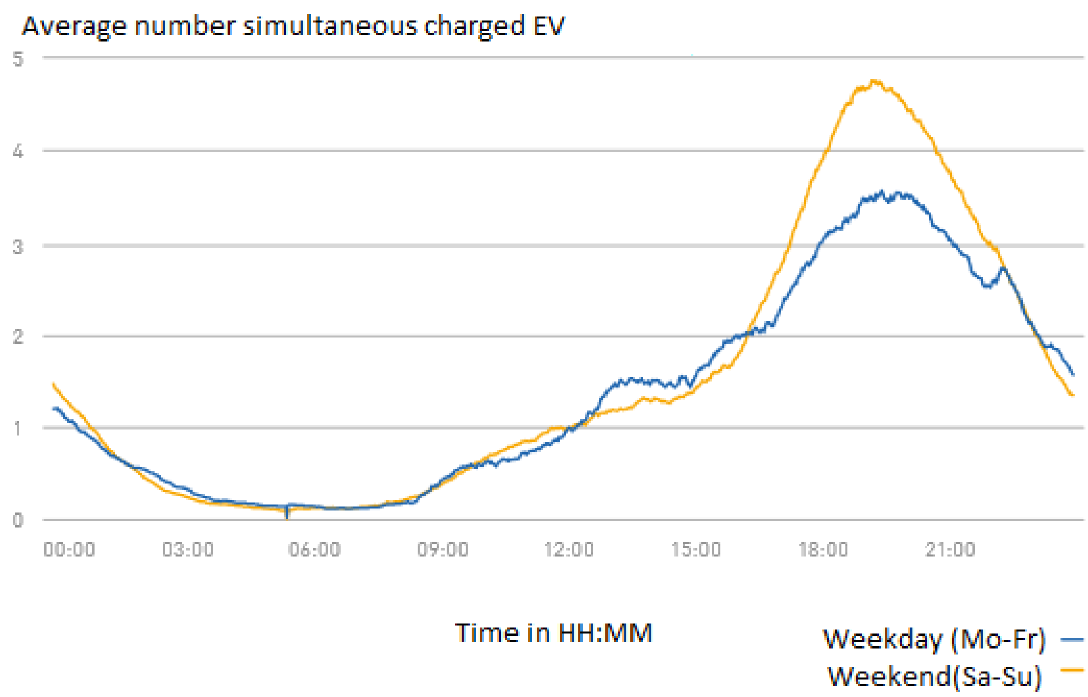

Figure 3.7: Number of simultaneously charged EV in specific time-stamps during project time [Net21a]

The conclusion is that the charging management is an essential technology in [Net21b] and [Net19b]. Centralized battery storages help to smooth load peaks, but aren't as helpful as a charging management. The impact is way too small, that already out of economic reason, an installation has to be viewed separately. But it is definitely a good extra support of the charging management system.

3.3 Integration of rural places in the grid

In the E-Chaussee scenario [Net21c] [Net21d], one electric circuit supplied eight households.

Chosen environment:
Structures in rural areas are very different from urban or suburban regions. 60% of the networks in Baden-Württemberg are located in rural regions. Characteristics are longer distances between connection points in the grid, higher number of occupants that are provided service by the same electric circuit. These two factors have a great influence on the quality of voltage. As seen in [Net19b], we had a potential difference of 4% in charging eight EV simultaneously, with a smaller electric circuit and shorter distance between the connection points. The longer the cable from consumer to the supplying transformer station, the higher the voltage fluctuations and the more likely it is that impermissible voltage band violations will occur. What free capacities does the power grid have? With the help of grid calculation software, simulations of the grid can be created in a very short time. But how does this work? First of all, the actual situation is considered without additional consumption of EVs. Now the task is to find out how many CPs or EVs the grid theoretically could accommodate before the permissible voltage band is violated or the power lines are overloaded. The circuit here will consist of two cables in order to perform a selective separation of single-phase and three-phase loads onto one cable. An important insight of the project was that usage patterns of rural users hardly differ from those in cities and suburbs.

In this section of rural places, used techniques are presented primarily. Figures aren't displayed as they are not necessary for the understanding of our problem statement. Important values captured can be seen in Chapter 4.

Technical approaches for the integration of e-mobility into the rural electricity grid.

- String regulator
- Centralized battery storage
- Charging management

In this case, we present the technical structure of this project, as relevant technical insights were already displayed in the two projects above and many information is periodic.

Transformer station provides power supply for E-Chaussee and is the interface between regional and local distribution networks.

A *String regulator* reacts to the voltage level in the circuit to raise or lower it as needed. The alternative would be a complete grid expansion, but this would be much more expensive. In rural grids, voltage is usually a bigger problem than capacity utilization of the power cable. This is due to the long lines, which then lose voltage from the beginning to the end.

Decentralised battery storage supplies the electric car with the help of a photovoltaic system.

Charging management. Charging processes are controlled by means of predefined schedules or real-time measured values from the electricity grid.

Some EVs require a minimum charging current to be able to start up again independently. This means that if the power is reduced too much, some vehicles will only charge again after the charging plug has been unplugged and then plugged in again.

Interval charging management constant switching of the charging power between two or more groups.

Cable distribution cabinets can detect voltage values in the network, in addition to straight direction voltage drop.

Central battery storage compared to the string regulator can achieve a positive effect on the voltage level by feeding in at the end of the string and reduce the total load of the circuit. This is a recurring technology from [Net19b].

Conclusion

In Conclusion, the presented charging management offers the highest potential for integrating a large number of EVs into the distribution network. We can easily throttle down the capacity even though the EVs are charged in time, as we have the suitable durability of EVs. The battery storages help to smooth load peaks. This is the first takeaway of our research. We will now proceed with chapter 4 and the design of our model.

4 Design

In this chapter, we describe the design of our model. First, the data will be extracted out of [Net19a] [Net21d] and [Net21a]. Those are derived and interpreted to setup our model and apply it to the computer science building at the University of Stuttgart.

4.1 Evaluation of data in projects

Which data has to be captured to evolve the model? The chosen parameters will be briefly discussed in this chapter. In Chapter 5, we will have a closer look, at which parameters are significant and used for our model.

General overview
Table 4.1 shows a short outline of the number of EV and installed CP in action.

Project	Number EV	Number of CP
Allee	11	10
Carree	45	58
Chaussee	8	8

Table 4.1: General overview

How long does it take to charge a car?
In Table 4.2, the average charging time to 100% SoC of an EV in the three different projects is displayed. The nearly exact same duration is visible. Certainly, as seen in Table 4.11, Table 4.12, and Table 4.13, those values are very superficial. Because of different charging behaviour, battery capacity and charging power, every EV should be evaluated by itself for an exact and precise result.

Project	Average charging time
E-Allee	2.5 Hours
E-Carree	2.5 Hours
E-Chaussee	2.6 Hours

Table 4.2: Average EV charging load estimation

Charging events/Time of arrival
In Table 4.3, we see consistent charging events/time of arrival in the evening hours. Many of the participants tend to charge their EV after work.

Project	Charging Events
E-Allee	19:00 h to 00:30 h
E-Carree	18:00 h to 22:00 h
E-Chaussee	19:00 h to 23:00 h

Table 4.3: EV charging events

What is the parking space factor?

In Table 4.4, parking spots and participants are displayed. Here, the context between parking spots per resident and number of CP can be derived.

Project	Parking spots	Participants
E-Allee	10	10
E-Carree	85	63
E-Chaussee	8	8

Table 4.4: Parking spots and number of participants

How often are EV charging simultaneously?

In Table 4.5, a clear trend toward a high probability of zero EVs charging is registered. Simultaneous charging events don't take place often in context to the percentages captured.

EV	Percentage
0	73%
1	21%
2	4%
3	1%
4	0.3%
5	0.1%

Table 4.5: Number of EV simultaneously at a charging point in the E-Allee

In Table 4.6, a clear trend toward a high probability of zero one or two EVs charging simultaneously is registered.

Number of EV	Frequency
0	42.1%
1-2	31.5%
3-4	12.4%
5-6	7.6%
7-8	3.8%
>8	2.6%

Table 4.6: Frequency of EV charging simultaneously in the E-Carree

In Table 4.7, a clear trend toward a high probability of zero EVs charging simultaneously is registered. Only in 20% of cases do we have one or two EVs charging simultaneously.

EV	Percentage
0	72%
1-2	20%
>3	8%

Table 4.7: How often EV are charged simultaneously in the E-Chaussee

Table 4.8 is an extension of Table 4.6 and Table 4.7 where we can see the all-time maximum of EVs charged simultaneously. Thus, we gain an understanding of approximately how many CPs are needed for a specific number of EV owners who want access to charge their vehicle. This value can be used to calculate the maximum workload (all of the CPs provide maximum charging power) the network connection has to provide. As an example, in the E-Carree we had 11 kW CPs and a maximum of 13 EVs charging simultaneously, which yields in a workload of 11kW*13 = 143kW.
For comparison only:
E-Allee: 22kw*8=176kW
E-Chaussee: 22kW*6= 132kW
Those are the values if we have a simultaneously factor of 1.

Project	Max
E-Allee	5 (50%)
E-Carree	13/58 (22.5%)
E-Chaussee	6/8 (75%)

Table 4.8: Maximum of simultaneous events

Which infrastructures do exist? (One-family house, row house, multi-family house, and public buildings, for example universities).
These are the environments taken into account in the projects.

- Residential area (E-Allee)
- Big housing area (E-Carree)
- Rural place (E-Chaussee)

Parking time

In Table 4.9, we see the average standing time at a CP. This value was only given in the E-Allee, but out of charging preferences overnight, the E-Carree and E-Chaussee should be in the same range.

Project	Durability
E-Allee	7.5 Hours
E-Carree	N/A
E-Chaussee	N/A

Table 4.9: Average durability

Charging points

In Table 4.10, the CP with their charging power is displayed. 22kW wall boxes were chosen in the E-Allee and E-Chaussee, as the E-Carree only supplied the EV with 11 kW.

Project	CP
E-Allee	22 kW
E-Carree	11 kW
E-Chaussee	22 kW

Table 4.10: CP charging intensity

Used EVs

In Table 4.11, Table 4.12, and Table 4.13, the chosen and used EVs and their individual characteristics are portrayed. We see completely different battery capacities, charging power and charging behaviour. This results in completely different charging and standing times. As discussed in Table 4.2, the value of charging time is really superficial, but is used to simplify our model.

Model of EV	Battery capacity	Charging power	Charging time	Range	Charging behaviour
VW e-Golf	35.8 kWh	7.2 kW (AC)	5.5 Hours (AC)	200 km	Two phase
BMW i3	33 kWh	11 kW (AC)	3 Hours (AC)	200 km	Three phase
Renault Zoe	41.5 kWh	22 kW (AC)	2.25 Hours (AC)	250 km	Three phase
Tesla Model S 75D	75 kWh	16.5 kW (AC)	6 Hours (AC)	400 km	Three phase

Table 4.11: Chosen EV in E-Allee

Model of EV	Battery capacity	Charging power	Charging time	Range	Charging behaviour
VW e-Golf	35.8 kWh	7.2 kW (AC)	5.5 Hours (AC)	200 km	Two phase
BMW i3	33 kWh	11 kW (AC)	3 Hours (AC)	200 km	Three phase

Table 4.12: Chosen EV in E-Carree

Model of EV	Battery capacity	Charging power	Charging time	Range	Charging behaviour
Nissan Leaf	40 kWh	4.6 kW (AC)	8.5 Hours (AC)	220 km	Single Phase
Renault Zoe	41 kWh	22 kW (AC)	2.15 Hours (AC)	250 km	Three phase

Table 4.13: Chosen EV in E-Chaussee

4.2 Setup of model

Which captured knowledge out of Chapter 3 and Section 4.1 can be used to answer the research question?

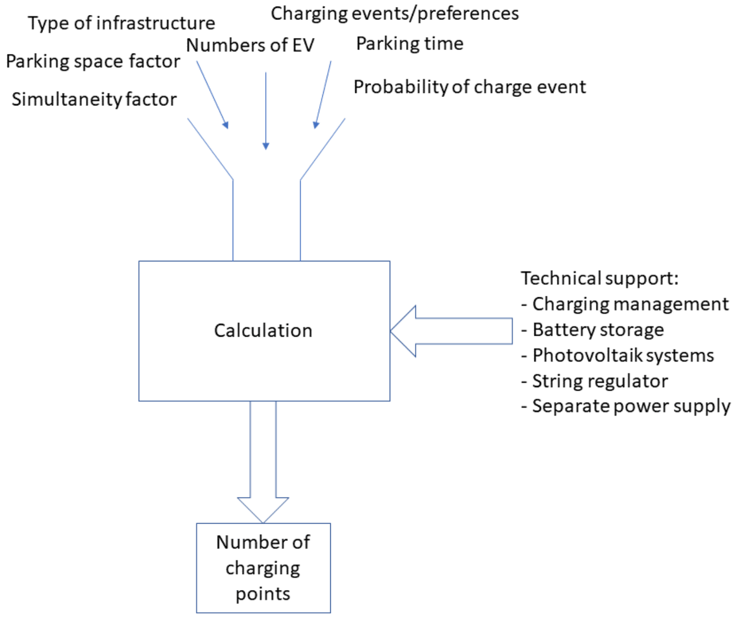

Figure 4.1: Updated model

As can be seen in Figure 4.1, in comparison to Figure 1.3, the various possibilities of technical support have to be included in our model to guarantee an optimal expansion of charging infrastructure. Furthermore, it is noticeable that the chosen parameters considered in early stages of the thesis changed due to project evaluation.

4.2.1 Calculation model simulation

Assumptions:

1. We have an average standing time, three times higher than the average charging time required. This allows us to use charging management in all cases. Surveys show that the majority do not feel restricted in their e-mobility (93% in [Net21a]).
2. If all cars can be charged in a distributed manner during this time, the grid connection can be throttled to 40 kW as in the E-Carree. (Ten EVs charging simultaneously in Figure 3.2 resulted in a voltage drop 4%)
3. Max CP = Max parking spots
4. Probability of charge event

What is the probability of a charge event?:
For all projects, we take the all-time peak of cars charging at the same time. As seen in paper [Har+18], 50-80% of charging events take place at home. We have implemented this scenario within all projects. 15-25 % take place at work and 10% on long journeys. We see the probability of a charging event at home is two and a half times more frequent than at work. This factor has to be calculated and viewed within our model. In general, we would have to investigate between the interconnection of simultaneous charge events at home (as in the projects) and simultaneous events at work, to calculate this factor. As we evaluated projects in private sectors especially at home we take this as our benchmark. In this case we have a probability factor of 1, as mentioned above a charging event at work takes place 2.5 times less. To simplify calculation we assume that we have half of charging events at work than at home. This results in a factor of 0.5. For the public sector we choose a factor of 0.2, as it's charging processes take place 5 time less than at home. So the factors are calculated in dependence on the private home sector.

How to choose technical support?
The choice of technical support is difficult to predict. As we discuss later a charging management is essential for old buildings, which have to be adapted to e-mobility. Battery storages assist the charging management to relieve the grid. In general the implementation of battery storages makes sense if enough space exists for installation. For new buildings we could directly plan to use an extra power supply cable as an installation for older buildings brings several challenges as discussed in [Net21a]. In addition to the extra power supply the charging management and battery storages can be implemented as well.

Algorithm 4.1 An algorithm for calculating a number of CP

```
1: procedure calculateCP
2: select area type:
     1: residential area, several single households
     2: urban agglomerations, big housing areas
     3: rural places, several single households
3: for area type do
4: take maximum of simultaneously charging events
5: divide step 4 by number of EVs used in projects
6: for new scenario do
7: determine number parking places
8: multiply step 5 result by step 7 result
9: calculate the number of charging points
10: multiply step 9 by the factor of probability for a charging event to take place
     1: for public sector (long journeys): 0.2
     2: for private type (home): 1
     3: for private type (work): 0.5
11: for estimate power supply needed do
12: select wall box with kW
     1: 11kW
     2: 22kW
13: multiply kW by step 9 result
14: choose technical support
     1: Charging management
     2: Battery storages
     3: Extra power supply cable
```

Algorithm 4.2 shows the developed model in accordance to our projects. First an area type has to be chosen, which is most similar to the new infrastructure to be adapted to e-mobility. Afterwards the maximum of simultaneously charging events has to be picked out of Table 4.8 and divided by the number of EVs in Table 4.1 to examine the ratio of maximum CP needed for a single EV. The result is multiplied by the number of parking spaces in the new scenario (We assume a concentration of 100% EVs and no petrol-engined vehicles). Now we have calculated the CP required for our scenario. As explained above the probability of a charge event must be integrated in the calculations as well. If this is done, we have the final number of CPs. In addition we can calculate the power supply with different wall boxes if we multiply by step 9 and choose technical support.

4.3 Applying the model on the computer science building at University of Stuttgart

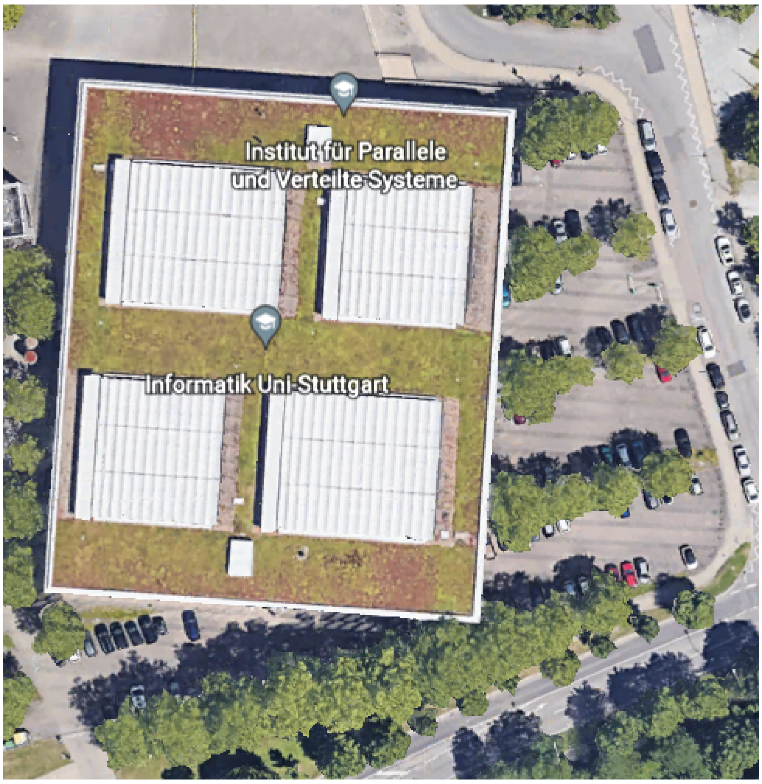

Figure 4.2: Top view of computer science building captured with Google Earth

Algorithm 4.2 Calculation of CP for computer science building at the University of Stuttgart

2: Select area type: urban agglomerations (E-Carree)
4: Maximum charging events: 13
5: CP/Overall EVs (13/45) = 0.288
7: Number of parking spots = 70
8: 0,288*70=15.4 CP // the value will be rounded up to 16
10: 16CP* 0.5 = 8 CP
12: Choose wall box 22kW
13: 22kW*8 = 176kW
14: Decision to be made

Check of interconnection between charging time and average durability

In state 14 we decide to use a charging management as in Figure 3.5. The EV needs a minimum supply of 5 kW at least as we mentioned the problems earlier if we fall below this border.

Given:

1. 5* BMW i3
2. 3* Renault Zoe
3. Power cap = 40 kW
4. Number CP = 8
5. SOC < 10%

The performance of a single EV follows from the power cap divided by the number of CP calculated.

$$\text{Performance single CP}: \frac{40kW}{8} = 5kW$$

Charging time also depends on charging behaviour and phases switching off at the end of a charging process. For convenience, phases are not included in the next formula. We want to calculate the standing time of an EV at a CP if it has under 10% SOC. This is our worst case scenario as the EV takes the maximum time to recharge to 100% SOC. The charging time for a BMW and Renault are shown next.

$$charging\ time = \frac{battery\ capacity}{charging\ power}$$

$$\text{BMW}: \frac{33kWh}{5kW} = 6.6h$$

$$\text{Renault}: \frac{41kWh}{5kW} = 8.2h$$

In conclusion this means we have a CP utilization of 100%, if we review the durability time at a CP in connection with office hours on workdays. From this it follows that we have a maximum flow rate of eight EVs with the power cap of 40kW. Therefore, we should raise the power cap to speed up charging processes.

Raise of power cap to 60 kW:

$$\text{Performance single CP}: \frac{60kW}{8} = 7.5kW$$

$$\text{BMW}: \frac{33kWh}{7,5kW} = 4.4h$$

$$\text{Renault}: \frac{41kWh}{7,5kW} = 5.4h$$

What we have to check is the possible voltage drop. In Figure 3.2 we saw a voltage drop of 4%. As we mentioned this was in range and therefore, this can be converted to our example. In our first try to use a charging management with a power cap of 40kW resulted in a maximum flow rate of eight EVs. This seems to be not realistic as probably more than eight out of 70 persons want to charge. In this case only one in nine could charge their EV. With an advanced power cap of 60kW the charging processes terminate earlier. In this scenario we would have a flow rate of approximately 16 EVs, which is twice as much as with a power cap of 40 kW. In [Net21a] we had a maximum load factor of 120% without a charging management. With the usage of charging management we had a maximum load of 60% of the main cable. This implies there would be enough space for other electrical consumers. Therefore, as we have less CP and maximum simultaneously charging events (maximum of 8 instead of 13) we can consider to use the main cable with a charging management. With the use of a battery storage, as seen in Figure 3.4 an additional smoothing of the workload curve is noticeable. If enough space for installation is given, a battery storage as presented in the projects can be installed to help relieve the grid. The calculation of our setup returns a recommendation of eight CP. This would result in a maximum power demand of 176kW (22kW multiplied by 8) if every car is charged simultaneously. We can easily adapt a charging management system in the current state of the art. As we have longer standing times from 08:00 h to 19:00 h (guiding value is the first lecture to last lecture in University), we can coordinate charge events on a longer time interval as in the E-Carree. We had an upper limit of 40 kW as seen in Figure 3.5, charging four EVs simultaneously. The upper limit has never been exceeded in three hours of charging. In our case of eight vehicles charged simultaneously, we let the charging management decide how to throttle the performance. Parking space factor has to be considered on network operator side to estimate the overall increase of output. If we would have a new building, I would recommend a separate power supply, as the power needed is already high. Due to potential future extension, we have a comfortable initial position.

5 Discussion

In this chapter, the evolved model will be discussed along with how it fits into the real world. All of the parameters chosen for our model have been derived out of the three projects analyzed.

Our discussion is divided into five parts, as different levels of the model have to be reviewed and discussed. One part is the discussion of the different area types chosen, another gives an insight into technical support to relieve the grid. Parameters viewed have to be discussed, as well as the parameters the model didn't consider but could be interesting for future research. The last part gives an assessment on using the model in real life.

As the ratio of combustion vehicles to EVs will become more unbalanced through the ages, it is necessary to discuss charging infrastructure. With steady increases in sales of EVs, more charging events will take place. Therefore, more CP are necessary to supply the vehicles with energy. Hence, it is essential to integrate CPs into the system, as it's the most common way to charge an EV. Other technologies, for example inductive charging are not very widespread yet.

5.1 Discussion of area types

The evaluation should focus on the transferability of projects or area types on other projects with same or similar structures and requirements.

The first surrounding included was the E-Allee [Net19b], which displayed a typical residential area with several single family houses, which is really common in city regions. A big transformation in e-mobility has to be expected as well, as we think of more and more people switch to urban grounds of big cities, for example to work. Netze-BW attributes to these areas a pioneering role in electric mobility as well in [Net19a]. In conclusion, this project is essential and sufficient for our analysis and development of the model.

In the underground car park scenario [Net21b], we had a big EV stock in a relatively small area. Netze-BW expects in the areas near urban agglomerations for there to be a rapid increase of EV. As we saw in Chapter 4, we had a maximum of 13 simultaneously charging EV with use of a charging management and an evaluation of the power supply cable, which offers us to apply this project this scenario to smaller scenarios of the same structures. For this reason, the [Net21b] is an important area for our model.

As rural places capture 60% of networks in Baden-Württemberg [Net21d], the necessity of this area considered in our model has no need to be discussed much. However, the captured data has to be viewed, which is only usable for similar grid structures as in this project. Recommendations for other networks can be derived. A transfer to any other rural network isn't possible, because of the differences between the number of occupants accessing the grid and the distances between the connection points in the grid (voltage drop).

As seen in paper [Har+18] 50-80% of charging events take place at home. We have implemented this scenario within all projects. 15-25 % take place at work and 10% on long journeys. This distribution has to be discussed as well. Do we need as much charging infrastructure, for example, at work than at home, where charging events are three times more frequent? This is an important factor as well in the dimension of charging infrastructure expansion. Therefore, if you take the data from the projects, it may be overdesigned for the public sector.

It is important to note is our related work was captured on German ground and conditions. Hence, it is difficult to transfer it to other countries, as there is a different EV stock, different political conditions (changeover to electric mobility not yet complete), and a variety of general network conditions across national borders [Fun+19]. Furthermore, factors for purchasing an EV are completely different [SCLF22].

In addition, differences between already given infrastructures and new ones to be developed have to be viewed, for example what profile of requirements and restrictions do we encounter? In already existing buildings, the structure to integrate charging infrastructure has to be viewed. In contrast, cable ways and cable cross sections can be dimensioned early enough for new buildings. Already existing buildings can be upgraded by technical support, for example with a charging management or battery storages to smooth the grid load. If enough residual capacity is left when connecting the residential building to the grid, charging columns can be installed without implementing a charging management. However, this is only possible with a small amount of CPs. The question here is whether this makes sense, since the trend of electric cars on the roads is steadily increasing. If more CPs are considered to be retrofitted in the future, the capacity limit will be reached quickly. For this, either the grid connection capacity must be increased or the charging processes must be coordinated in such a way that no overload occurs. Accordingly, there is no alternative to a charging management system. Other chargers in the buildings can't generally be displayed. Since each type of infrastructure has a different number of consumers, possibly also very powerful consumers, large differences can arise. If the energy consumption is high, there is generally less load to install charging columns. This was also evident in the comparison of the household profiles with charging an EV and without charging an EV, as seen in Figure 2.3.

5.2 Discussion of technical support

The technical tools used and deployed will be addressed in this chapter. This will include what can be used where, and which tools only have a small effect. There is a strong connection between these tools and the existing infrastructure. If cable cross-sections can no longer be adapted, a charging management system is indispensable. Especially in larger projects, where many consumers access the grid in a short time. We saw the success in every project reviewed, especially in connection with longer standing times where the charging management offers more time to charge the EV to relieve the load factor in the grid. The decentralized energy storage, as well as the centralized energy storage presented are technologies that helps to smooth the workload, in comparison to the charging management it has not the big impact. Each owner of a CP should decide about the installation of an external battery storage by themselves, for example on grounds of economic reasons to charge their car with solar energy. Another factor is the shortage of space where problems could occur to install extra battery storage. A separate grid connection in large charging parks is recommended on the basis of the evaluated data in [Net21a]. This could be used in big public charging parks, where we could also have electric trucks. This is also necessary in order to be completely flexible and prepared for the future. It may be that there will be other technologies that depend on the electricity grid and that will lead to an even greater load in the future.

5.3 Discussion of chosen parameters

Charging events and preferences of EV drivers give a perfect indication of how our charging infrastructure needs to be dimensioned. As can be seen in Table 4.3, the charging events largely take place in the evening hours. This brings us directly to the next point, the factor of charging EVs simultaneously [VBE]. How often EVs are charged simultaneously over the process seen in Table 4.8 presents interesting insights. The factor captured in [Net21a] of a maximum of 13 allocated CPs simultaneously we can calculate the ratio of CP installed and how many CPs needed, even as an approximate value to other scenarios. The available parking space is a important factor too. On the one hand, we have an upper limit of the maximum number of CPs that can be installed in relation to the maximum number of parking spaces. If we have a higher density of people, this implies a higher likelihood that people will own a car here, especially an EV in view of future terms. The parking space factor, this means spots per resident, is a sign as well for the number of CPs to be installed. Empirical studies, for example determined a parking space factor of 0,43 [Net21a] for Baden-Württemberg. This results in a competition to access a CP and charging events change due to lack of CPs, depending on the time of the day.

Another important parameter is the standing time and accordingly average durability. One important fact is that electric vehicles in the private sector usually have much longer standing times than in the public sector. This means they have more time to charge a car than it actually needs. This offers the necessary flexibility to control charging processes through a charging management system. Furthermore, the arrival of an EV at the charging station is an important factor as well. If we take the workplace as an example, the curve will rise from 08:00 h to 16:00 h. Since there is a clear tendency to notice that people charge when they park the car longer, both can be transferred to the workplace and thus integrated into the model. Most EV owners usually tend to charge their EVs after coming back from work during evening hours. Parking time in our projects can be transferred to similar standing times as when going to work. What has not been investigated here is fast charging, for example at shopping centres. Here, shorter standing times are more likely, which limits the use of charging management. If the load is limited so as not to overload the grid, the cars will hardly be charged at all while not being moved.

5.4 Discussion of potential parameters missed

Now the question is which parameters were not covered by the tests, and therefore still have to be included. What other parameters would be needed to be safely prepared for the future?

The type of CP is not considered in our model. As can be seen in charger difference, slow CPs and fast CPs have a different influence on the grid. For example, the voltage drop is already much higher with fast CPs. The installation of fast CPs is therefore rather limited, as the peaks go faster in a way that we can't explore given the limitations of this thesis. This means the number calculated of needed CPs represents chargers of 11 kW and 22 kW, which were used in the projects, and could not be replaced with Tesla superchargers for example.

In order to carry out a more detailed analysis and to make the model more precise, [Chr22] reviewed the charged energy per charging process, the arrival and number of EVs at CPs, and how long they stay at a CP.

Charging characteristics of EVs are also important. As seen in Table 4.13, Table 4.12, and Table 4.11, we have one-, two-, or three-phase charging of EV. Therefore EVs are charging with more or less power, which results in a different load factor on the grid. The costs of a single CP should also be considered [H S22]. As well as providing different charging capacities with different kW. So, the calculation of how many slow-charging or fast-charging points should be integrated specifically. Another key factor is at which time the vehicles are on the road. How does traffic flow impact the usage of a CP [LZJL12]? If we use the technologies available on the market, for example V2G, could there be a possibility to smooth the workload as we saw it with a centralized battery storage in Figure 3.3 and therefore install more charging points? Different age groups also have different charging habits. Some users also forget to charge overnight. The impact of several short trips made, shopping behaviour, initial SOC, this was all viewed in [KFS+21]. In general, we have many different charging characteristics as charge patterns, references, battery capacity, SOC, time of arrival, and route derivations due to traffic congestion.

5.5 Does the model fit in the real world?

The main focus of the projects was on the analysis of the use of technical aids and how they relieve the grid. As utilisation of power cables, charging management, and substation as it is described in [LWL13], to for example minimize the voltage drop in the grid. This evaluation was conducted in order to determine how best to integrate a larger number of EVs into the network, and accordingly the implementation of charging stations. In each of the projects, the success was seen through the intelligent charging management system. Furthermore, one of the most important indicators was the factor of

$$\frac{number\ simultaeonously\ charged\ EV\ max}{number\ of\ parking\ spots}$$

However, this formula must also be set as a function of the people who have the possibility to access the CPs. Therefore, the actual need of CPs for a certain number of EV owners can be determined for every kind of scenario. Especially considering the three scenarios evaluated in the projects, which are really common in reality, the model can be used as a rough guide. As described in the section above, various parameters are not covered by the model. Further data could be collected and included here. Since we have evaluated private sectors in the projects, it is difficult to apply the model to public structures, because of different standing times of the cars. In public charging, processes have to be faster, which results in higher utilisation of the grid. Overall, we have to evaluate all levels of our discussion and which parameters are important for a specific scenario.

6 Conclusion

Gasoline is one of the biggest resources in demand in the world. We see the greatest consumption in the transport sector every day. However, this resource is limited and as can be seen now, could be heavily dependent on political conflicts. A switch to electrification in the transport sector is necessary. This change will make us less dependent on petrol and will also have an effect on global warming. The current start of electromobility shows that this is key to improve a nation's economy and guarantee people's quality of living. Especially in view of achieving greenhouse gas neutrality by the year 2045, an adaptation of cities with EVs is needed worldwide. However, it is not enough just to put EVs on the roads, but also to supply them with electricity. An electric car, or the driver of an electric car, should always be offered the possibility of charging within the possible distance it can travel. This requires a sensible charging infrastructure that satisfies the people. It must be determined which are the best urban locations to implement CPs, but an even more important factor is how many charging stations should be installed in total. The model described here gives insight into the factors that need to be considered in order to accommodate the appropriate number of EVs. Another side effect of the expansion of CPs is that people's trust in e-mobility is gathered. With fast progress in the expansion of chargers, people trust in the technology. Hence, it is important to adapt the charging infrastructure to the number of EVs in stock. The first part of the thesis introduced the topic to contrive technical backgrounds. In context, we discussed several technical mechanics to implement charging infrastructure in an appropriate way. The second part of the thesis implements the model, and our algorithm developed. We saw the attributes integrated in the model as well as the interaction with technical support. The trend in every project was that the charging management is the way to go in the case of charging infrastructure being installed. In this connection we conclude following:

- The number of EVs to be integrated is small means, already existing electric supply is sufficient enough.
- Average number of EV to be integrated means, upgrade existing electric supply with charging management and optional integration of battery storages, which speeds up the charging process and relieves the grid.
- High number of EVs to be integrated means, energy supply via separate line connector and integrated charging management, because of the high requirement of energy by multiple EVs.

We conclude that the developed model and captured data are a good advice to a certain degree. Our approach in the example showed that the number of CPs calculated is realistic in comparison to our references in the projects. Hence, it is a good guiding principle.

Outlook

Primarily, future work should focus on the extension of our model developed. Due to rapid propagation of EVs, it is possible that some of the parameters, now considered in our model, need to be changed or adapted to enable progressing of electromobility.
Second, in the charging time we used average values, which is very imprecise, when it comes to different EV models, as they charge with different characteristics and the EVs itself have completely different characteristics. Here, a fragmentation and analysis of different performance data can be implemented.
Third, it should be investigated which factors improve our model. As we discussed, several parameters are missing in our model, which could be integrated with more research. Fourth, we analysed private sectors in the projects evaluated. The model could be adapted to public structures as well with the right parameters and captured data. As mentioned, long journeys capture 10% of the charging events.
Fifth, possibly other technical support could be evaluated to put parameters in the model that we didn't currently consider.
Sixth, it should compare results with other field tests organized in the past.
Furthermore the assumptions in the thesis, as economic aspects, can be integrated as well. We focused on the implementation of the structure itself, but not the cost at all for several CPs, and there may be difficulties in the expansion of cable ways, et cetera.
Another interesting aspect would be to research V2G technology. The vehicles equipped with V2G could smooth the network load by releasing energy to the grid, so it could have an effect similar to a decentralized energy storage. The need would be to install more CPs than needed, as the EV has to be plugged into a CP all the time.

Bibliography

[ACE21] ACEA. “Electric cars: 10 EU countries do not have a single charging point per 100km of road”. In: 2021. URL: www.acea.auto/press-release/electric-cars-10-eu-countries-do-not-have-a-single-charging-point-per-100km-of-road/ (cit. on p. 19).

[Age] E. E. Agency. In: (cit. on p. 17).

[Buna] D. Bundesregierung. “EU-Umweltrat: Nur noch CO2-frei fahren”. In: (). URL: https://www.bundesregierung.de/breg-de/themen/europa/verbrennermotoren-2058450 (cit. on p. 17).

[Bunb] D. Bundesregierung. “Verkehr”. In: (). URL: https://www.bundesregierung.de/breg-de/themen/klimaschutz/verkehr-1672896 (cit. on p. 17).

[Bun21] D. Bundesregierung. “Generationenvertrag für das KLima”. In: Deutsche Bundesregierung, 2021. URL: https://www.bundesregierung.de/breg-de/themen/klimaschutz/klimaschutzgesetz-2021-1913672 (cit. on p. 17).

[Chr22] D. U. S. Christopher Hecht Jan Figgener. “Analysis of Electric Vehicle Charging Station Usage and Profitability in Germany based on Empirical Data”. In: 2022, pp. 1–11. DOI: 10.48550/arXiv.2206.09582. URL: https://doi.org/10.48550/arXiv.2206.09582 (cit. on p. 52).

[Ene22] I. EnergyAgency. “Global EV Outlook 2022”. In: 2022. URL: https://iea.blob.core.windows.net/assets/ad8fb04c-4f75-42fc-973a-6e54c8a4449a/GlobalElectricVehicleOutlook2022.pdf (cit. on p. 19).

[Fun+19] S. Á. Funke et al. “How much charging infrastructure do electric vehicles need? A review of the evidence and international comparison”. In: vol. 62. 2019, pp. 224–242. DOI: 10.1016/j.trd.2019.10.024. URL: https://doi.org/10.1016/j.trd.2019.10.024 (cit. on p. 50).

[GFJ18] T. Gnann, S. Funke, N. Jakobsson. “Fast charging infrastructure for electric vehicles: Today’s situation and future needs”. In: vol. 62. 2018, pp. 314–329. DOI: 10.1016/j.trd.2018.03.004. URL: https://doi.org/10.1016/j.trd.2018.03.004 (cit. on p. 17).

[H S22] A. B. H. SALIMI H. OUADI. “Genetic algorithm for sizing optimization of the EV chargers in a smart building”. In: 2022, pp. 414–419. DOI: 10.1016/j.ifacol.2022.07.347. URL: https://doi.org/10.1016/j.ifacol.2022.07.347 (cit. on pp. 17, 27, 52).

[Har+18] S. Hardman et al. “A review of consumer preferences of and interactions with electric vehicle charging infrastructure”. In: vol. 62. 2018, pp. 508–523. DOI: 10.1016/j.trd.2018.04.002. URL: https://doi.org/10.1016/j.trd.2018.04.002 (cit. on pp. 44, 50).

[IEA22a] IEA. “Global electric car stock, 2010-2021”. In: IEA, 2022, p. 46. URL: https://iea.blob.core.windows.net/assets/ad8fb04c-4f75-42fc-973a-6e54c8a4449a/GlobalElectricVehicleOutlook2022.pdf (cit. on pp. 17, 19).

[IEA22b] IEA. "Global electric car stock, 2010-2021". In: IEA, 2022. URL: https://www.iea.org/data-and-statistics/charts/global-electric-car-stock-2010-2021 (cit. on p. 18).

[KFS+21] M. Kavianipour, F. Fakhrmoosavi, H. Singh, M. Ghamami, A. Zockaie, Y. Ouyang, R. Jackson. "Electric vehicle fast charging infrastructure planning in urban networks considering daily travel and charging behavior". In: *Transportation Research Part D: Transport and Environment* 93 (Apr. 2021), p. 102769. DOI: 10.1016/j.trd.2021.102769. URL: https://doi.org/10.1016/j.trd.2021.102769 (cit. on p. 52).

[LWL13] Z. Liu, F. Wen, G. Ledwich. "Optimal Planning of Electric-Vehicle Charging Stations in Distribution Systems". In: *IEEE Transactions on Power Delivery* 28.1 (2013), pp. 102–110. DOI: 10.1109/TPWRD.2012.2223489 (cit. on p. 52).

[LZJL12] Z.-f. Liu, W. Zhang, X. Ji, K. Li. "Optimal Planning of charging station for electric vehicle based on particle swarm optimization". In: *IEEE PES Innovative Smart Grid Technologies*. 2012, pp. 1–5. DOI: 10.1109/ISGT-Asia.2012.6303112 (cit. on p. 52).

[Mic22] E. V. MichaelODioha June Lukuyu. "Guiding the deployment of electric vehicles in the developing world". In: 2022, p. 3. DOI: 10.1088/1748-9326/ac765b. URL: https://doi.org/10.1088/1748-9326/ac765b (cit. on p. 17).

[Net19a] Netze-BW. "E-Mobility-Allee". In: Netze-BW, 2019, pp. 1–44. URL: https://assets.ctfassets.net/xytfb1vrn7of/6gXs8wiRSF0E2SqkwSq406/fc1c9430ba88b81c31e399242b09b17e/20191217_BroschuereE-Mobility_210x275mm_100Ansicht.pdf (cit. on pp. 24, 25, 29–33, 39, 49).

[Net19b] Netze-BW. "E-Mobility-Allee". In: Netze-BW, 2019, pp. 92–101. URL: https://www.netze-bw.de/e-mobility-allee (cit. on pp. 27, 29, 33, 36–38, 49).

[Net21a] Netze-BW. "NETZlabor E-Mobility-Carré". In: Netze-BW, 2021, pp. 1–56. URL: https://assets.ctfassets.net/xytfb1vrn7of/oGRGcuHKm3eaKEA2LDGic/3bd954234bf9339220bc6d6e6512cc6d/netzlabor-e-mobility-carree-abschlussbericht.pdf (cit. on pp. 23, 33–36, 39, 44, 48, 50, 51).

[Net21b] Netze-BW. "NETZlabor E-Mobility-Carré". In: Netze-BW, 2021, pp. 1–44. URL: https://www.netze-bw.de/unsernetz/netzinnovationen/netzintegration-elektromobilitaet/e-mobility-carre (cit. on pp. 27, 33, 36, 49).

[Net21c] Netze-BW. "NETZlabor E-Mobility-Chaussee". In: Netze-BW, 2021, pp. 1–56. URL: https://www.netze-bw.de/unsernetz/netzinnovationen/netzintegration-elektromobilitaet/e-mobility-chaussee (cit. on pp. 27, 37).

[Net21d] Netze-BW. "NETZlabor E-Mobility-Chaussee". In: Netze-BW, 2021, pp. 1–73. URL: https://assets.ctfassets.net/xytfb1vrn7of/LKFK7LIHxW9nYxFlS1QxC/b8fff50d34043775189cd35c46ed9671/e-mobility-chaussee-abschlussbericht.pdf (cit. on pp. 37, 39, 49).

[Pat15] W. F. Patrick Jochem Sonja Babrowski. "Assessing CO2 emissions of electric vehicles in Germany in 2030". In: 2015, pp. 68–83. DOI: 10.1016/j.tra.2015.05.007. URL: https://doi.org/10.1016/j.tra.2015.05.007 (cit. on p. 17).

[PBC+20] D. Pevec, J. Babic, A. Carvalho, Y. Ghiassi-Farrokhfal, W. Kettera, V. Podobnik. "A survey-based assessment of how existing and potential electric vehicle owners perceive range anxiety". In: 276.12 (2020), pp. 1–12. DOI: 10.1016/j.jclepro.2020.122779. URL: https://doi.org/10.1016/j.jclepro.2020.122779 (cit. on p. 19).

[SCL21] S. Secinaroa, D. Calandraa, F. Lanzalonga. "Electric vehicles' consumer behaviours: Mapping the field and providing a research agenda". In: 2021, pp. 92–101. DOI: 10.1016/j.jbusres.2022.06.011. URL: https://doi.org/10.1016/j.jbusres.2022.06.011 (cit. on p. 17).

[SCLF22] S. Secinaro, D. Calandra, F. Lanzalonga, A. Ferraris. "Electric vehicles' consumer behaviours: Mapping the field and providing a research agenda". In: *Journal of Business Research* 150 (Nov. 2022), pp. 399–416. DOI: 10.1016/j.jbusres.2022.06.011. URL: https://doi.org/10.1016/j.jbusres.2022.06.011 (cit. on p. 50).

[VBE] VBEW. "Elektromobilität". In: (). URL: https://www.vbew.de/energie/energie-fuer-bayern/mobilitaet-fuer-bayern/elektromobilitaet (cit. on p. 51).

All links were last followed on November 23, 2022.

Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

Stuttgart, 22.11.2022

place, date, signature