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Faculty of Mechanical Engineering

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***Technical and economical optimization of public car-charging
infrastructure via determination of key performance indicators
and identification of potential for improvement***

Thesis to obtain the academic degree
Master of Science (M. Sc.)

Submitted by
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Affidavit

I hereby declare in accordance with § 18 Para. 4 Nr. 7 APO THl by my signature, that this thesis is my own work, that I have not presented it elsewhere for examination purposes and that I have not used any sources or aids other than those stated. I have marked verbatim and indirect quotations as such.

Ingolstadt, 16. June 2023

Simon Müller

Abstract

The passenger transport sector is undergoing a transition towards electric mobility to reduce CO₂ emissions. One commonly mentioned challenge that could hinder the success of electric vehicles is the availability of public charging infrastructure.

This work focuses on optimizing public car infrastructure from both technical and economic perspectives, providing valuable insights for decision-makers and operators of charging infrastructure.

It begins with a general analysis of mobility behavior in Germany, followed by an examination of charging locations.

Subsequently, the stakeholders involved in public car charging infrastructure are identified, and their goals are used to construct a set of key performance indicators (KPIs). These KPIs enable a comprehensive assessment of public car charging infrastructure.

The identified KPIs, including Economic Efficiency, Utilization, and Usability, are then applied to an exemplary set of public charging points, showcasing the practicality of these metrics, and offering valuable insights into their current situation.

The findings from the application of the KPI set, such as the critical economic situation of the assessed public charging infrastructure, are integrated with potential improvement opportunities and concrete measures to achieve the set goals.

The work emphasizes the importance of charging demand and utilization rate as key factors for the success of the evaluated charging stations, while also highlighting various other aspects that can enhance the performance of any public charging station.

Keywords: public charging infrastructure, electric mobility, performance indicators, economic efficiency, utilization, usability, performance enhancement

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List of abbreviations

| | |
|-----------|---|
| AC | – Alternating current |
| BDEW | – Federal Association of Energy and Water (Germany) |
| BEV | – Battery electric vehicle |
| CI | – Charging infrastructure |
| CP | – Charging point |
| CS | – Charging station |
| DC | – Direct current |
| DSO | – Distribution system operator |
| EV | – Electric vehicle |
| EVSE-ID | – Electric Vehicle Supply Equipment Identification |
| HGV | – Heavy goods vehicle |
| HPC | – High power charging |
| KPI | – Key performance indicator |
| MiD | – Mobilität in Deutschland |
| MSP | – Mobility Service Provider |
| OFI | – Opportunity for improvement |
| PFI | – Potential for improvement |
| PSP | – Payment Service Provider |
| PV | – Photovoltaic |
| QR | – Quick Response (code) |
| THG-Quote | – Treibhausgasminderungs-Quote |
| UX | – User-experience |
| V2G | – Vehicle to grid |
| VW | – Volkswagen |

List of units and formula symbols

| | | | |
|-----|-----------------|--------|--------------|
| a | – Year | P | – Power |
| A | – Ampere | E | – Energy |
| ct | – Euro cent | t | – Time |
| € | – Euro | η | – Efficiency |
| km | – Kilometer | | |
| kW | – Kilowatt | | |
| kWh | – Kilowatt-hour | | |
| kWp | – Kilowatt peak | | |
| m | – Month | | |

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1 Introduction

1.1 Presentation of the topic

The share of battery electric vehicles (BEV) in Germany is rising. In 2022, BEV accounted for 17.7 % of the newly licensed cars, rising from a share of 13.6 % in 2021 and 6.7 % in 2020 (cf. Kraftfahrt-Bundesamt, 2023) (cf. Kraftfahrt-Bundesamt, 2022b). This significant change is driven by multiple measures aiming towards a future passenger transport sector with less CO₂-emissions.

These measures, though seemingly small on paper, have profound implications not only for drivers and their habits but also for the energy sector. The transport sector which was self-contained before is now being coupled to the electricity sector.

This shift begins at the customer level, where charging of electric cars replaces refueling. Subsequently, grid operators play a crucial role in providing the necessary grid capacity, while energy plants must supply the additional energy required for electric vehicles (see Figure 1). In a theoretical future scenario where 100 % of passenger cars in Germany are BEV, this would amount to 100 TWh of energy per year (cf. Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz, 2020b).

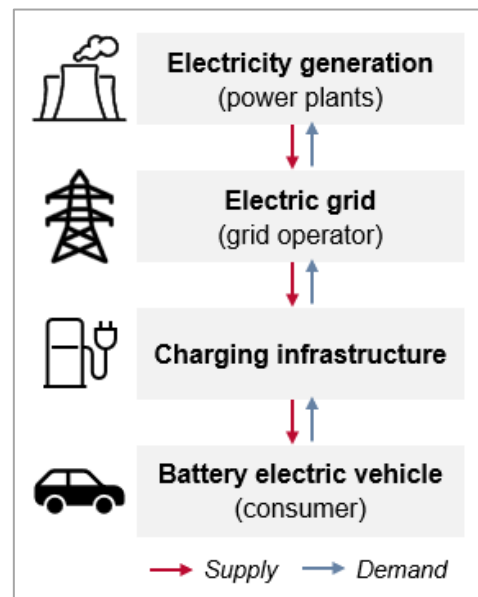


Figure 1 - Levels of energy supply for battery electric vehicle (own representation)

But despite all the challenges that may appear with this significant change, electric mobility holds promise for the future of transportation, at least in mainstream mobility, because of its potential advantages in reducing CO₂-emissions, compared to conventional combustion cars.

However, one doubt, that is mentioned on a regular basis when it comes to causes that could hinder the success of electric vehicles, is the availability of public charging infrastructure. A study conducted in 2020 with 1,200 interviewees revealed that, after high acquisition costs and limited range, the availability of public charging infrastructure ranked as the third reason for not purchasing a BEV (cf. Martin Kords, 2022).

As of January 1st, 2023, there were approximately 67,000 normal charging points and over 13,000 high power charging points available for public charging in Germany (cf. Bundesnetzagentur, 2023). Behind each charging point stands a so-called charging point operator (CPO), a new player in the ecosystem between grid operators and BEV drivers.

Major CPOs in the high power charging (HPC) sector in Germany include EnBW, IONITY or Fastned.

Municipal utilities play a significant role in operating normal charging points that typically operate with alternating current (AC) and have a power output of around 11 kW to 22 kW.

Some companies also operate their own public or semi-public charging infrastructure for their employees, such as AUDI AG, which has installed over 400 public charging points around its headquarters in Ingolstadt.

Like any other CPO, AUDI AG operates within a delicate balance between charging point availability and utilization rate, which is not only an economic consideration but also an ecological one. Since electric mobility has the aim to be more environmentally compatible than means of transportation using fossil fuels it is only logical that the necessary infrastructure also needs to be assessed under environmental and sustainable aspects. Due to the continuing growth of electric vehicles the optimum in this field needs to be reassessed continuously.

1.2 Status quo and target definition

The installation of the first public charging points at AUDI AG headquarters took place around 2013. By the beginning of 2023, the number of operational charging points had surpassed 2,200, with over 400 of them accessible to the public. This growth in numbers not only highlights the progress made but also signifies the need for a fresh perspective on the subject. Initially, the focus was primarily on establishing new charging points to ensure charging availability and gain insights into the technology. However, as the number of charging points has significantly increased, the charging landscape has reached a state of normality, necessitating a reassessment and adaptation of the main objectives.

An optimized operation of the system needs to be focused. The goal of this master's thesis is to analyze the existing public charging infrastructure in the vicinity of AUDI AG headquarters in Ingolstadt.

Subsequently, by identifying the factors that impact the operation and conducting an analysis of the current charging system, key performance indicators (KPIs) will be aggregated to pinpoint areas for future operational improvements. This approach aims to approximate an optimum for the charging infrastructure.

1.3 Structure of the thesis

The initial phase of the study will provide a theoretical introduction to the topic, laying the foundation with insights into mobility behavior, the charging sector, and various charging solutions (Chapters 2 – 3). Subsequently, a comprehensive analysis of relevant factors, such as utilization and cost, will be conducted to establish a set of KPIs that facilitate the assessment and optimization of (public) charging infrastructure (Chapters 4 – 5).

Once the general framework is established, the identified KPIs will be applied to analyze the existing public charging infrastructure at AUDI AG (Chapter 6). This analysis will primarily rely on data obtained from the charging infrastructure's backend, which will provide valuable information on charging processes, user behavior, utilization patterns, and energy consumption. Additionally, inputs from the CPO (AUDI AG) regarding acquisition and maintenance costs will further enhance the understanding of the current system.

By thoroughly examining the present KPI values for different subsystems or groups of charging points, a comprehensive assessment of the system's current state will be presented. Each KPI will then be scrutinized to identify areas with potential for improvement (Chapter 7). In conclusion, specific optimization measures will be outlined for each performance category, such as enhancing economic efficiency and utilization.

2 Theory of the charging sector

This chapter serves to provide a comprehensive overview of the charging sector, establishing a foundation for understanding the necessity of charging infrastructure. It begins by analyzing the mobility behavior of individuals in Germany to derive insights into potential charging requirements. Furthermore, it delves into the various types of charging locations and offers a glimpse into the future trajectory of the charging sector.

By presenting these essential elements, this chapter establishes the groundwork for the subsequent analysis and optimization of charging infrastructure, empowering readers with a comprehensive understanding of the subject matter.

2.1 Definitions, distinction, and general information

This section aims to establish the necessary definitions for key terms that will be utilized in the subsequent chapter and consistently throughout the thesis.

- A **charging process** is defined as the successful transfer of energy from any kind of charging infrastructure to a battery electric vehicle. It is important to note that while this process often involves payment, it is not necessarily a requirement.
- **Home charging** refers to the charging process that occurs in a private context and location. It involves a charging infrastructure operated by a private individual, typically the owner of the BEV. Home charging processes are usually not connected to a payment process, such as when using a private wall box at a single-family house.
- **Public charging**, on the other hand, involves charging processes that take place in public locations. The charging infrastructure is operated by a company or institution and is accessible to any BEV driver. Public charging processes typically involve a payment process, such as public charging station at a public parking lot or along a highway.
- **Semi-public charging** refers to a situation where the charging infrastructure is not owned by the BEV driver, but access to the charging point is restricted (e.g., a wall box at an apartment building operated by the property owner).
- The term **charging station** (CS) is most commonly used in the public charging sector to describe a location where charging is possible. A keyword **charging pole** refers to the pole-shaped charging hardware, which is a subset of the charging station. A charging station can consist of several charging poles.

The term **charging point** (CP) refers to the smallest subset, representing an access point where a car can be charged. Some charging poles have two or more charging points. In most cases, these terms can be used as synonyms.

In some cases, especially when discussing quantities, it is important to know the difference, for example when a charging station consists of five charging poles, each with two access points (charging points), resulting in a total of ten charging points ($5 \times 2 = 10$).

2.2 Mobility behavior and charging needs

Normally, every charging process is preceded by a mobility requirement. Charging is never performed in isolation, but rather as a response to the need or desire for transportation. Consequently, this chapter will conduct a qualitative analysis of mobility (behavior) and the corresponding charging needs. The subsequent section, Chapter 2.3, will establish a link between these needs and the available charging solutions.

Battery electric vehicles, which require recharging, are primarily utilized in the passenger car sector. It is worth noting that other forms of transportation, such as trains, may also rely on electricity but employ different technological approaches (e.g., overhead contact lines) that eliminate the need for a separate charging process.

The existing charging infrastructure predominantly caters to battery electric passenger cars, reflecting their current dominance in the market. However, for other vehicle types, such as heavy goods vehicles (HGV), the charging infrastructure is still in the early stages of development and planning (cf. Nationale Plattform Zukunft der Mobilität, 2021, pp. 4–6). Hence, this mobility assessment will primarily focus on passenger cars and their associated charging demands. (With the development of the battery electric vehicle market and the expansion into other sectors, this assessment needs to be reevaluated.)

Dominance of passenger car in personal transport

According to the *Mobilität in Deutschland (MiD)* report, in 2017, cars, as a transport medium, accounted for 57 % of all ways and 75 % of all passenger kilometers traveled (cf. Follmer and Gruschwitz, 2019, p. 13). The Federal Environment Agency also highlights the predominance of motorized cars in passenger transportation (cf. Umwelt Bundesamt, 2022a).

Currently (2022), a significant share of these cars runs on petrol or diesel. Calculations of the Federal Environment Agency show that until 2030, around 16 million passenger cars and light duty vehicles running on fossil fuels need to be replaced with electric vehicles to reach the set climate goals in the traffic sector (cf. Umwelt Bundesamt, 2022b). Given the assumption that battery electric vehicles will fulfill similar purposes as their fossil predecessor, it is relevant to examine current mobility profiles.

Energy demand of battery electric passenger cars

On average, a passenger car in Germany covers a distance of 14,700 km per year (cf. Nobis and Kuhnimhof, 2019, p. 4). By considering an average energy consumption of a BEV in

kWh/100km, the demand for this mobility need can be approximated (in terms of energy). The ADAC provides a current list of BEV with electric consumptions ranging from 16.7 to 30.9 kWh/100 km (cf. Wieler, 2022). Based on these figures, it would require approximately 2,455 to 4,542 kWh of energy to cover the annual distance of 14,700 km.

Approximation of necessary charging power

By combining the available charging times with the energy need, a minimal charging power can be deducted. The charging power of charging equipment is the main feature from a technical point of view.

For the purpose of a preliminary theoretical approximation, no assumptions about the availability of charging infrastructure will be made, but only the hypothesis that the car can only be recharged when it is not in motion (parking state).

According to a study, cars are in a parking state for an average of more than 23 hours a day (cf. Nobis and Kuhnimhof, 2019, p. 5). With the said assumptions and an average charging efficiency of 0.95, a minimal charging power of less than 1 kW can be deducted, as shown in Equation 1.1.

$$P = \frac{E}{t} = \frac{\frac{4,542 \text{ kWh/a}}{0.95}}{23 \text{ h/d} \times 365 \text{ d/a}} = 0.57 \text{ kW} \quad (1.1)$$

It is important to note that the applicability of this theoretical value to reality is limited, as the calculations are based on averaged values, assume a uniform mobility demand, and do not consider the availability of charging infrastructure. However, it provides an initial indication that the lower threshold for charging power will likely be determined by factors such as charging efficiency (standby losses), driver comfort, and the availability of charging infrastructure, as they play a bigger role than the simple energy requirement.

Trip purposes

The next step is to delve deeper into differentiation and examine how varying assumptions impact the expected charging solutions and properties, such as charging power. To accomplish this, a look will be taken at different possible charging locations. The *MiD-Report* provides a breakdown of seven different driving purposes, which will allow to draw conclusions about possible charging locations. Figure 2 illustrates the shares of passenger car travels associated with these trip purposes. The related starting or end points for these trip purposes, such as work, or public places like a shopping center, are possible locations for charging.

One location that is not explicitly depicted in the Figure is "Home." Unlike work or leisure, it is not considered a trip purpose but serves as a major starting or ending point for drives. On average, more than 20 hours a day the car is parked at the domicile.

Additionally, the study finds that in small towns or villages, 90 % of the cars park on private property, whereas in metropole areas 50 % of the cars park in public areas (cf. Nobis and Kuhnimhof, 2019, p. 5).

The nature and ownership structure of the parking spot (private/public) are expected to significantly influence the resulting charging solution.

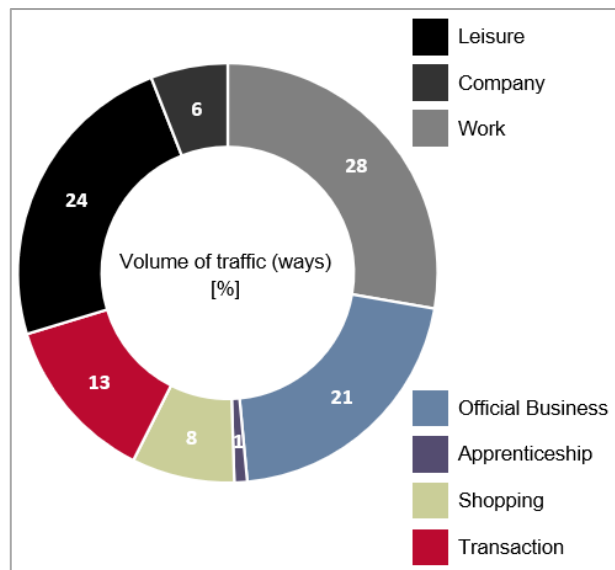


Figure 2 - Distribution of passenger car traffic regarding trip purposes (based on Nobis and Kuhnimhof, 2019, p. 71)

Another important location to consider in this assessment is the workplace. Its significance is evident from the fact that about two-thirds of the traffic activity of the working population on weekdays is work-related (cf. Nobis and Kuhnimhof, 2019, p. 6). Approximately 50% of all passenger car journeys are related to work, including work commutes, official business, and apprenticeships (cf. Nobis and Kuhnimhof, 2019, p. 71).

Further locations are associated with leisure trips (24 %) and shopping or other transactions (21 %) (cf. Nobis and Kuhnimhof, 2019, p. 71). Due to the diverse nature of these trip purposes, a detailed examination of the related parking locations would result in a large number of sub-categories (e.g., shopping mall parking lot, theater parking spot, hospital parking deck). However, for the purpose assessing possible charging locations (and for the further derivation of charging solutions) this granularity is unnecessary. It will be demonstrated that adopting a broader categorization of these parking spots as public is sufficient, since they have a similar requirement profile.

Long distance travels

An exception to the previously discussed approach relates to the distance traveled, rather than being deducted from trip purposes.

Especially for long distance travels the charging need is fundamentally different than at other public places. On a long-haul route, one of the main aims of the driver is to reach its destination as quickly as possible. If the range of the BEV is smaller than the total travelling distance to be covered, interim charging becomes necessary. Recharging the battery of the car is then the main reason for the stop – which is the first difference to general public charging where the

charging part is not necessarily the main reason for a stop (but more of an add-on to the public parking spot).

Furthermore, the aim of reaching the destination soon automatically translates into the main objective of the long-distance charging need: minimizing the charging time. The time required for the charging process and the amount of energy transferred to the car become essential key performance indicators. This marks the second significant difference compared to other public charging needs.

Although drives longer than 100 km only account for 1 % of total drives, they contribute to 25 % of the overall traveled kilometers (cf. Nobis and Kuhnimhof, 2019, p. 4). Because of the high relevance of these cases (for the driver) and the specific profile of the charging need this category will be considered separately in the subsequent steps.

2.3 Charging locations and solutions

This chapter provides descriptions of the charging solutions related to the location categories summarized in Figure 3.

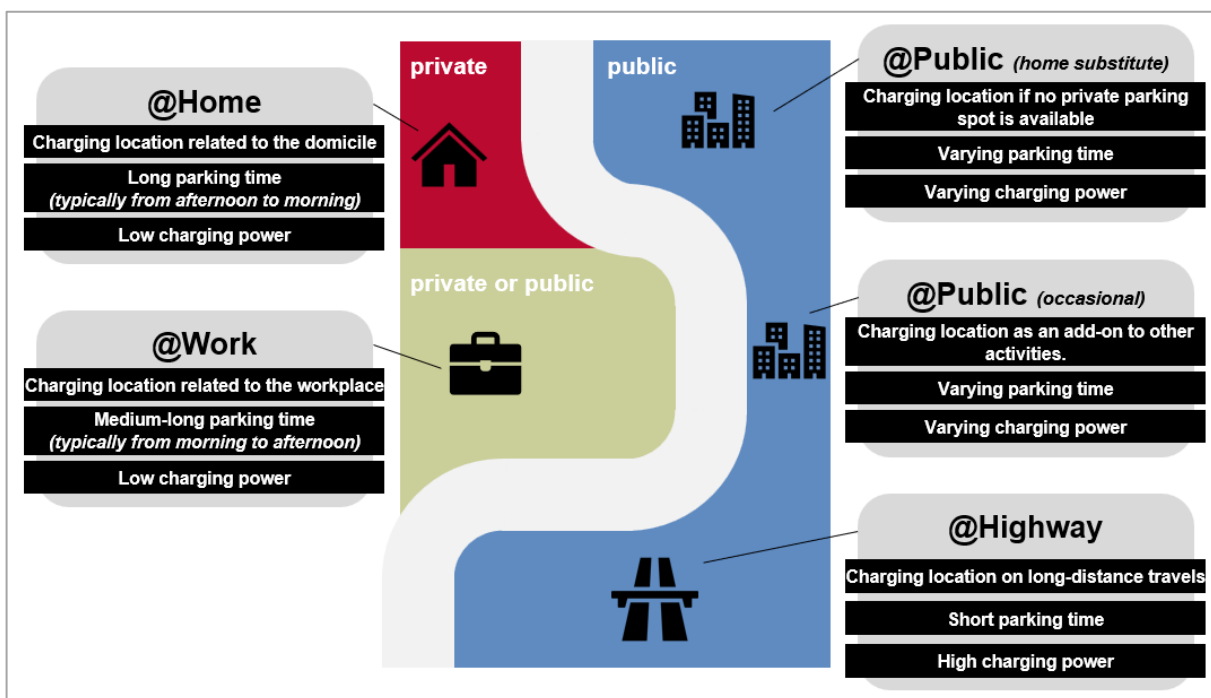


Figure 3 - Charging locations (own representation)

Home charging

The first and most important charging location is “at home”. Parking spot and charging equipment are privately owned and generally not open for public access. In 2020, the German National Centre for Charging Infrastructure claimed that up to 85 % of all charging processes happen at home (cf. Nationale Leitstelle Ladeinfrastruktur, 2020b).

The VDA expects the share of private charging processes to descend to 60 – 70 % with proceeding market penetration of BEV (cf. Verband der Automobilindustrie e.V., 2019, p. 3).

The importance of said location can also be seen from another fact. On average, 75 % of private passenger cars in Germany are parked on a private parking space. However, for the subgroup of BEV, the share is significantly higher at 92 %.

That means in this stage of transition to electric mobility, BEV are particularly beneficial and appealing to users who have the convenience of charging at home (cf. Nobis and Kuhnimhof, 2019, p. 80). The data indicates that drivers without access to private parking spaces, which are necessary for a private charging infrastructure, are more hesitant to purchase a BEV as they rely on public charging infrastructure.

Compared to other options, home charging offers the highest reliability and convenience for EV drivers. Additionally, it provides the opportunity to integrate the battery electric vehicle into the home energy (management) system.

A common use case is overnight charging, where the car is connected to the CS after work and left charging until the next morning. Due to the extended parking duration, the required charging power with alternating current (AC) is typically low, ranging from 3,7 – 11 kW.

Work charging

The next category, “*at work*”, encompasses the charging infrastructure that enables the employees to charge at their workplace. Depending on the employer and the ownership structure for the CS, access to the charging point may be restricted or public.

Studies indicate that the workplace is the second most important location for charging (in terms of frequency), following home (cf. Wietschel et al., 2022, p. 7) (cf. EVBOX, 2022, p. 55).

Moreover, according to the Fraunhofer-Institute, charging *at work* significant potential for emission reduction in the transportation sector. In a typical scenario, the vehicle is connected to the CS in the morning before the start of work and remains connected until the end of the workday in the afternoon, complementing the typical charging times *at home*. The flexibility in the timing of the charging process allows for the direct utilization of electricity generated from photovoltaic (PV) plants, thereby facilitating emission reduction (cf. Keller et al., 2022, p. 30).

The expected parking duration and the resulting charging power are comparable to the home use case.

Public charging

If private charging equipment is not available and the option to recharge *at work* is not accessible, a public charging station (CS) serves as a substitute for home charging. This scenario is particularly relevant in metropolitan areas where 50 % of cars are parked in public spaces (cf. Nobis and Kuhnimhof, 2019, p. 5).

The classic use case for this scenario is known as "Laternenparker" or street parking. In this case, the BEV driver chooses a public parking spot near their residence that is equipped with an electric charging infrastructure. The CS is installed at the roadside.

For public charging locations, the parking duration and charging power are similar to overnight parking at home (11-22 kW AC). However, there are a few differences that may cause discomfort for the driver, including the distance to the residence, potential time restrictions for the parking spot, and uncertainty about the availability of the CS.

To address the potential discomfort, another option for public charging as a substitute for home charging has been introduced, known as the charging hub. These hubs are located in urban areas and offer high charging powers (~150 kW or more), utilizing infrastructure working with direct current (DC). Instead of extended parking times with low charging power, the charging hub provides a short stay with high charging power. Unlike other public charging processes, the charging event at a hub is the main purpose of the visit or is closely related to it, reducing the impact of free-rider effects.

If the charging hub is the sole charging opportunity for a customer the visit will be repeated periodically (e.g., once a week) to fulfil the mobility needs. According to the German National Centre for Charging Infrastructure in 2030 those urban charging hubs could account for ~ 16 % of all publicly charged kilowatt hours (cf. Nationale Leitstelle Ladeinfrastruktur, 2020a, p. 68).

The utilization of the before mentioned public home substitute is depending on its attractiveness for the BEV driver as well as the mobility profile and the availability of other public infrastructure which coincides with other activities and enables occasional charging.

This occasional charging “*at public*” heavily relies on the free-ride effect, where the charging event is seen as an additional service during other activities such as shopping or visiting a restaurant. The associated public charging location serves as the customer's parking spot.

In line with this, the assessment of the German National Centre for Charging Infrastructure suggests that BEV users will not charge their vehicles significantly longer than their retention time at a public place (cf. Nationale Leitstelle Ladeinfrastruktur, 2020a, p. 42). This means that the vehicle is disconnected from the charging infrastructure when the main activity concludes, regardless of the amount of energy transferred or the car's state of charge. Charging serves as an add-on to the primary transaction, such as shopping.

Highway charging

The last charging location is related to long distance travels and commonly occurs “*at highways*” or at transport axes.

To facilitate quick stops, the CSs (at highways) are equipped with high power infrastructure of up to 350 kW (DC), similar to the charging hubs in urban areas. However, due to the distinct requirements for highway charging this location is hardly comparable to other public charging facilities. Assessments conducted by the German Federal Cartel Office and the European Commission indicate that this differentiation between highway charging and other public charg-

ing not only makes sense from a charging solution point of view but also from a market stand-point. They also recognize that the charging needs of BEV drivers at destinations like shopping centers are distinctly different from the needs of those recharging their vehicles on a highway (cf. Bundeskartellamt, 2021a, pp. 17–18) (cf. European Commission, 2019, p. 45).

2.4 Development of the charging sector in Germany until 2030

Following the logic derivation of different charging locations and the qualitative description of the charging solutions, this chapter will give a quantitative overview of the development and significance of the charging sector in Germany retrospectively and in the projected period until 2030.

As previously mentioned, the charging infrastructure is closely linked to the mobility requirements fulfilled by a battery electric vehicle. Therefore, the left side of Figure 4 illustrates the growth of the BEV fleet volume in Germany from 2013 until 2022 (cf. Kraftfahrt-Bundesamt, 2022a). Starting around 2018, a clear rise in BEV numbers can be seen. Together with that the quantity of public charging points is displayed from 2017 until 2022 (cf. Bundesnetzagentur, 2022b).

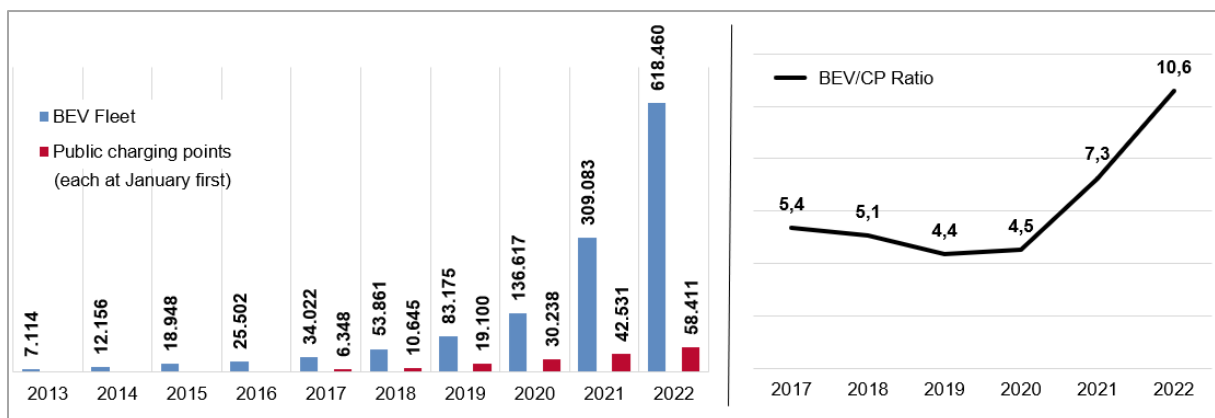


Figure 4 - Development of BEV-Fleet and public charging points in Germany next to BEV/CP Ratio (own representation based on Kraftfahrt-Bundesamt, 2022a and Bundesnetzagentur, 2022b)

Compared to the vehicle development which rises exponentially the infrastructure grows more linearly. That fact can also be seen in the ratio between BEV and public CP displayed in the right part of Figure 4.

It shows how many BEV share one public charging point in theory. As a guide value the European *Alternative Fuels Infrastructure Directive* from 2014 calls for a proportion of ten or less BEV for each public charging point (cf. *Directive 2014/94/EU on the deployment of alternative fuels infrastructure*. European Parliament and Council of the European Union, 2014).

The graph indicates that this threshold was already surpassed in early 2022, with approximately eleven cars competing for each public charging point (coming from 4.4 cars in 2019).

The strategy for sustainable mobility of the German federal government aims at 15 million BEV and one million public charging points operational by 2030 (cf. Presse- und Informationsamt

der Bundesregierung, 2022), which would result in an increased ratio of 15 BEV per charging point.

However, the German National Centre for Charging Infrastructure predicts that the current trend (of 2019–2022) will continue until 2030, with approximately 20 cars per public charging point. They argue that this may not necessarily be a problem due to two main factors. Firstly, they anticipate better availability of private charging infrastructure, which would alleviate the burden on public charging infrastructure. Secondly, they observe an increase in the charging power of vehicles, which leads to shorter charging times and reduces the number of charging points needed for the same number of BEVs (cf. Nationale Leitstelle Ladeinfrastruktur, 2020a, p. 5).

The statement of Timo Sillober, former chief sales officer of EnBW, a major operator of public charging infrastructure in Germany, supports this perspective. Sillober believes that to meet the demand for public charging infrastructure in 2030, approximately 130,000 to 150,000 high-power charging (HPC) points are needed, rendering the government's goal of one million public charging points outdated. Sillober justifies his assessment by pointing to technological advancements and changes in user behavior, among other factors (cf. Timo Sillober, 2023).

Jan Strobel from the Federal Association of the Energy and Water Industry (BDEW) shares a similar view, stating that the rapid deployment of HPC stations has led to a significant increase in installed charging power, thereby rendering the government's goal obsolete (cf. Schaal, 2023).

The report on charging infrastructure after 2025/2030 (Nationale Leitstelle Ladeinfrastruktur, 2020a) provides a broader perspective on this topic. The development and need for public charging infrastructure is evaluated for six different scenarios. One major variable that influences the public setup is the number or availability of private charging stations, as mentioned before. In the reference scenario, the German National Centre for Charging Infrastructure estimated that there would be 7,068,000 charging points available at the private residence in 2030 (cf. Nationale Leitstelle Ladeinfrastruktur, 2020a, p. 64).

Tracking the number of private charging points until and around the present year 2023 is not as straightforward as tracking public charging points because it is not reported. However, an indication can be derived from the number of applications for the KfW support program 440, which subsidized the purchase of a charging stations or “wall boxes” for residential buildings. Between November 2020 and October 2021, a total budget of 800 million euros was issued to promote the installation of approximately 900,000 charging points (cf. Nationale Leitstelle Ladeinfrastruktur, 2021b). The outpayment of the subsidy was only granted after the completed installation.

When combined with the quantity of private charging points that were set up before the support program or abstained from it, a total number of over 1,000,000 private charging points can be estimated.

Newer initiatives and support programs of the Federal Ministry of Transport are either directed at other target groups, such as municipalities, or focused on different use case, such as high power charging locations. For example, the “Deutschlandnetz” aims to establish 1,000 new high power charging locations with around 8,000 charging points to make HPC nationwide available (cf. Nationale Leitstelle Ladeinfrastruktur, 2021a).

The development of the HPC segment is also one variable in the aforementioned report on *charging infrastructure after 2025/2030*. The Figure below (Figure 5) shows four of the studied scenarios, including the number of private and public charging points, as well as the quantity of charging points *at work*. In addition to the standard or reference scenario, the influence of low or high availability of charging infrastructure “*at home*” is displayed. The last scenario evaluates the influence of additional HPC hubs in urban areas.

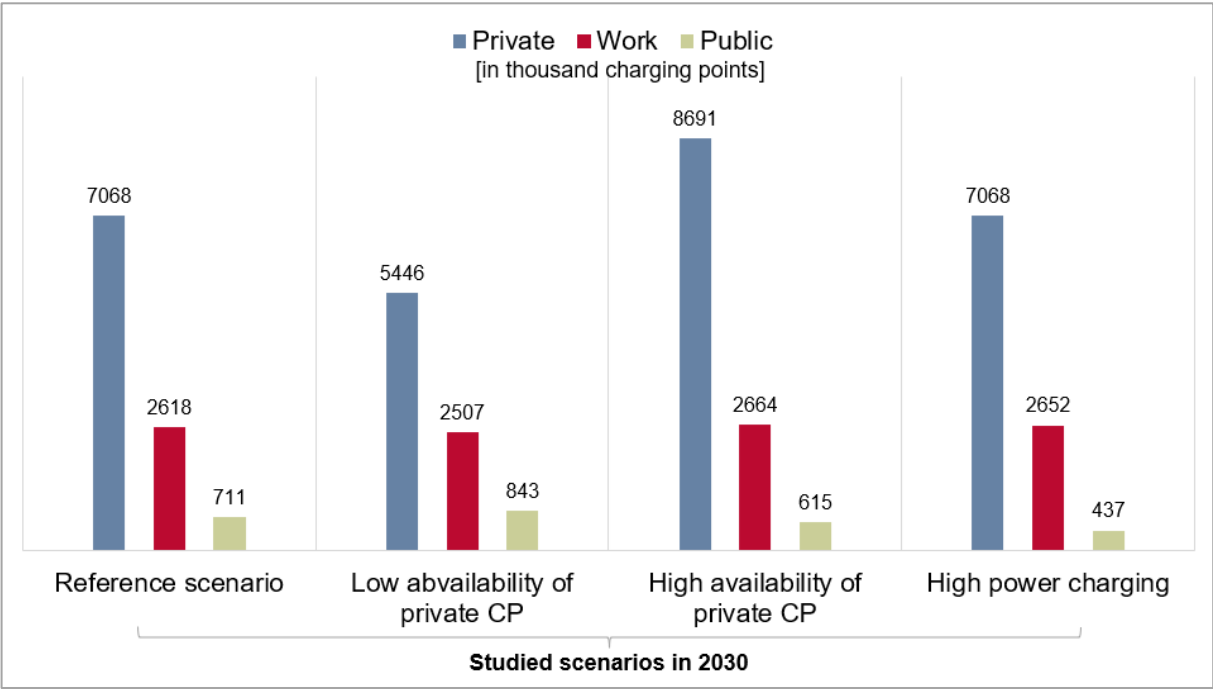


Figure 5 - Need of charging infrastructure in Germany in 2030 (based on Nationale Leitstelle Ladeinfrastruktur, 2020a, p. 64)

The key findings of this comparison are, on the one hand, that additional private charging infrastructure relieves the burden on public charging locations and, conversely, it becomes more essential if fewer private CPs are available. On the other hand, it can be observed that charging at urban HPC locations can significantly decrease the overall number of needed public CPs, from 711,000 to 437,000 (cf. Nationale Leitstelle Ladeinfrastruktur, 2020a, pp. 64–65).

Energetic development

Independent of the ratio between public or private charging points, the amount of energy needed to charge the BEV fleet is a significant factor. In 2020, the Federal Environment Ministry estimated that if the entire passenger car fleet (45 million) consisted of BEV, the electricity demand would be 100 TWh, approximately one sixth of Germany's the current gross electric consumption (cf. Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz, 2020a).

Additionally, an assessment of Germany's future electricity consumption was conducted on behalf of the Federal Ministry for Economic Affairs and Energy. The research indicated that in 2030, electric road mobility will consume around 70 TWh of electricity, with approximately 44 TWh attributed to electrified passenger cars. In 2018, when around 100,000 battery electric passenger cars were in use, they were responsible for 0.3 TWh of electricity. Thus, the traffic sector is the main driver of the growing electricity demand in Germany (see Figure 6). The second largest contributor to the increased demand is the additional 35 TWh needed for heat pumps in 2030 (cf. Kemmler et al., 2021, pp. 2–3).

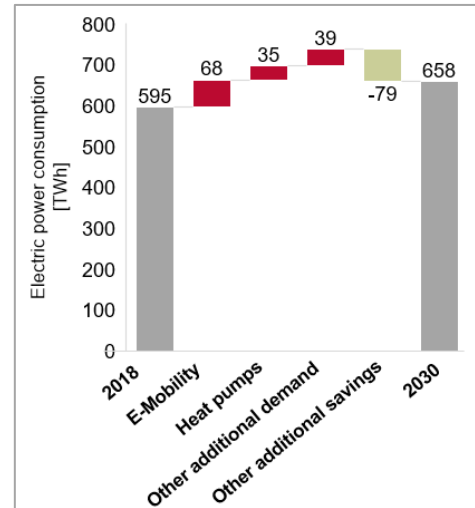


Figure 6 - Development of gross electric consumption in Germany (own representation based on Kemmler et al., 2021, p. 4)

The reference scenario of the report on *charging infrastructure after 2025/2030* predicts that in the year 2030, more than 12 TWh per year will be recharged at home, complemented by 8 GWh loaded at the workplace and around 10 TWh of electricity at public charging stations. Charging hubs in urban areas as a subgroup of the public charging infrastructure will be the emporium for about 1.5 TWh per year, as will the hubs at highways (cf. Nationale Leitstelle Ladeinfrastruktur, 2020a, p. 68).

A subsequent analysis examines the average amount of transferred energy per charging point per day (see Figure 7). Regardless of the simulated scenarios, the average daily energy transfer at home ranges from 5.1 to 5.2 kWh. In the workplace, the daily demand is nearly double, ranging from 8.8 to 10.3 kWh. For urban charging hubs, the range is between 161.5 and 222.1 kWh per connector per day, while for highway hubs, it falls between 197.0 and 236.4 kWh. At other public charging stations, such as customer parking or roadside locations, the daily recharge volume varies from 24.3 to 40.6 kWh (cf. Nationale Leitstelle Ladeinfrastruktur, 2020a, p. 69).

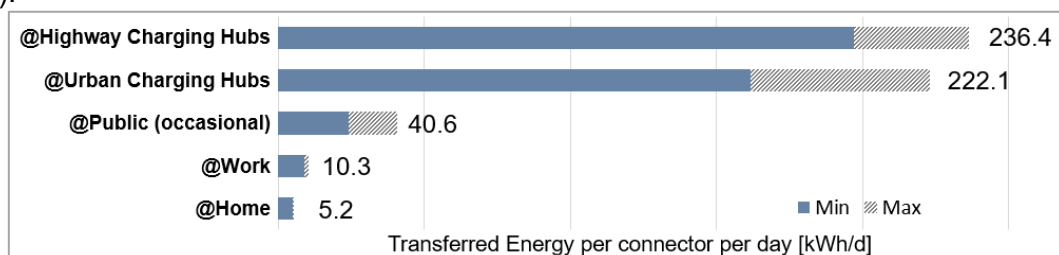


Figure 7 - Average transferred energy per connector in 2030 (own representation based on Nationale Leitstelle Ladeinfrastruktur, 2020a, p. 69)

3 Further theory of the public charging sector

After the general assessment of mobility behavior, charging locations for electric vehicles, and the development of charging infrastructure, this chapter will take a closer look on public charging infrastructure.

The *Charging Station Decree* defines every charging point as publicly accessible if it is located in public road space or if “the parking space associated with the charging point can actually be used by an indefinite or only generally identifiable group of people” (cf. *Verordnung über technische Mindestanforderungen an den sicheren und interoperablen Aufbau und Betrieb von öffentlich zugänglichen Ladepunkten für elektrisch betriebene Fahrzeuge*. Bundesministerium für Wirtschaft und Energie, 2016). Conversely, this means that public charging infrastructure must allow access to the charging point for all individuals without limitation to a specific group. This definition applies (or can apply) to the before mentioned charging locations or use cases of the “public home substitute”, “occasional public charging”, “highway charging”, and “charging station at work”. For the last category, a semi-public operation scenario is also possible where the charging stations are only available for employees. If this is the case, the regarding charging points are not considered public since the employees are a specifically defined group. The common characteristics, as well as the relationships of public charging infrastructure within the charging sector, will be shown in the following chapters.

3.1 Structure of the public charging ecosystem

The public charging ecosystem has many participants as shown in Figure 8. A successful charging process requires the transfer of both energy (red arrows) and a substantial amount of information (black arrows). To facilitate this, a comprehensive chain of participants must be established and effectively coordinated.

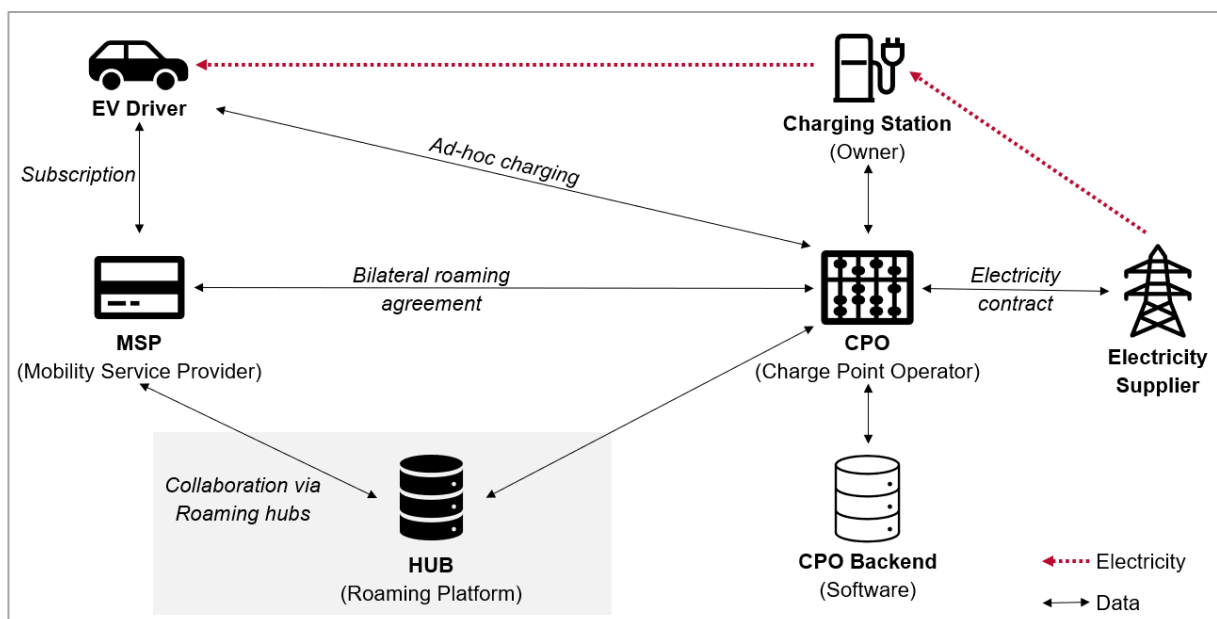


Figure 8 - Structure of the public charging ecosystem (own representation)

Electric vehicle driver

The electric vehicle driver (EV driver) serves as the initial and driving participant in the chain. Based on their charging requirements (see Chapter 2.2), the charging infrastructure is dimensioned. The various mobility profiles and the use cases for different charging locations – with public charging being one of them – were shown in Chapter 2.3. Public charging infrastructure can be regarded as an option available to the EV driver, which they will seek out if it aligns with their specific situation.

Charging station

If the driver, or then customer, relies on public facilities, their primary interaction occurs at or with the charging station. Electric energy is transferred from the charging point to the car, and the payment processing takes place (see more in Chapter 3.3).

As of January 2023, there are approximately 80,000 installed public charging points in Germany, each labeled with an individual Electric Vehicle Supply Equipment Identification (EVSE-ID). Out of those EVSE-IDs, more than 13,000 belong to high power charging points (cf. Bundesnetzagentur, 2023).

The theoretic ratio between publicly installed charging points and licensed BEV is one of the characteristics that allows for comparing the development of charging infrastructure across different markets or over time. In Chapter 2.4, a ratio of around eleven BEV per public connector in Germany was shown as of the beginning of 2022.

Charge Point Operator

In most cases, but not all, the owner of the charging infrastructure also acts as the Charge Point Operator (CPO). The German *Charging Station Decree* § 2 Nr. 8 defines a CPO as the entity „that in consideration of legal, economical and actual circumstances acts with determining influence on the operation of a charging point” (*Verordnung über technische Mindestanforderungen an den sicheren und interoperablen Aufbau und Betrieb von öffentlich zugänglichen Ladepunkten für elektrisch betriebene Fahrzeuge*. Bundesministerium für Wirtschaft und Energie, 2016).

In 2022, the *Charging Station Register* listed 4,813 different CPOs for the public charging stations in Germany (cf. Bundesnetzagentur, 2022a). Those CPOs can establish charging networks. The five largest CPOs, in terms of the number of charging points, namely EnBW mobility+ AG and Co.KG, E.ON Drive GmbH, EWE Go GmbH, Westenergie Metering GmbH, Stromnetz Hamburg GmbH, collectively operate just over 10,600 charging points (cf. Bundesnetzagentur, 2022a), which corresponds to 15 % of the public charging infrastructure in Germany.

This highlights the high fragmentation of the market, with many CPOs operating at regional level, such as municipal energy suppliers. In the subset of public charging infrastructure on highways, which primarily focuses on high power charging levels shows, a more concentrated

oligopolistic competition can be observed. Major participants in this field in the German market are Ionity, EnBW, Fastned, Allego or E.ON.

Electricity supplier

One key requirement for a CPO is to establish a contract with an electricity supplier to ensure a reliable energy source for the charging station. Due to their position in the market, many energy suppliers leverage their expertise to become CPOs themselves. According to the German Federal Cartel Office, approximately 80 % of the charging stations are provided by energy suppliers (Bundeskartellamt, 2021b, p. 10).

CPO Backend

If the number of operated charging infrastructure reaches a certain threshold, the use of a CPO Backend becomes essential. This backend software enables the operation and monitoring of the charging stations. It allows for the configuration of settings for different users or user groups, as well as adjustments of tariffs. In a few specific cases, the backend may not be necessary, such as when the charging station is not the primary focus but an additional service in the main field of operation (e.g., single public charging station at a supermarket). In such cases, it may also coincide with the situation where the customer is not billed for energy transferred.

Mobility Service Provider

If the charging process is not free of charge (as in most cases), EV drivers have various options for payment.

The first and most common option is to use a Mobility Service Provider (MSP), sometimes also referred to as E-mobility Service Provider (EMP). The MSP negotiates different charging prices with CPOs and then consolidates them to offer customers a standardized charging tariff across all participating CPOs. This provides with the advantage of knowing the pricing, even if they are not familiar with a particular CPO. Additionally, they can use the same payment method, such as an RFID card issued by the MSP, at different stations, eliminating the need to register with each individual CPO. Chapter 3.3 will discuss other payment methods and the MSP-CPO relationship via roaming agreements.

It is worth mentioning that in some cases, CPOs also operate as MSPs or vice versa. For example, EnBW is a company that not only operates multiple charging points but also offers an MSP-solution. It is important to note that their MSP tariff provides payment options for public charging in general, not limited to EnBW charging stations.

The market structure of the public charging sector in Germany is characterized by the complex relationships among all market participants, unlike the more familiar dependencies in the fueling sector. Additionally, the sector involves the processing of a significant amount of information.

3.2 Charging station decree

The legal obligations, primarily of the charge point operator, are outlined in the *Charging Station Decree*. This decree includes requirements such as the obligation to register public charging stations with the regulator, which in Germany is the Federal Network Agency. It also sets standards to ensure interoperability between charging infrastructure and electric vehicles.

Additionally, the decree provides essential definitions for the operation of charging infrastructure, including the threshold for “fast charging”, defined as “> 22kW” (cf. *Verordnung über technische Mindestanforderungen an den sicheren und interoperablen Aufbau und Betrieb von öffentlich zugänglichen Ladepunkten für elektrisch betriebene Fahrzeuge*. Bundesministerium für Wirtschaft und Energie, 2016). These definitions will be referenced throughout this thesis.

3.3 Payment and pricing

Ad-Hoc Payment

As previously mentioned, customers have various options for payment during the charging process. One of these payment methods is known as “Ad-Hoc Charging”.

According to § 4 of the *Charging Station Decree*, CPOs are required to offer this payment solution. As the name states this option is designed for spontaneous charging events or cases where the EV driver does not want to enter into a long-term contract with any party.

For a single charging event, the primary parties involved in the transaction are the EV driver and the CPO directly. To facilitate the payment of an “*Ad-Hoc Charging event*”, the CPO can provide either an established card payment service or a web application that customers can access via smartphone. The latest edition of the *Charging Station Decree* makes the card payment option compulsory for all charging point going into operation on or after July 1st, 2023 (cf. Bundesnetzagentur, p. 1).

In the case of the web application solution, a Quick Response (QR) code is placed on each charging station. It is important to note that exceptions to the Ad-Hoc requirement only apply to public charging stations where the energy is provided free of charge. This scenario does not apply to commercially operated stations.

MSP payment

Another and more common method is facilitated by an MSP (as described in Chapter 3.1). In this scenario, the end-user has already entered a contract before the charging process takes place. The primary parties involved in this contract are the EV driver and a Mobility Service Provider of their choice. This arrangement allows the customer to make payments via smartphone or with a personalized RFID-Card provided by their MSP at different charging stations, without the need to share personal or payment-related data with each new CPO.

In addition to handling data exchange, the MSP also sets the prices for the customer, ensuring consistency across charging location.

The necessary contractual relation between the MSP and CPO can be achieved in two ways. The first is through a *bilateral roaming agreement*, which defines the conditions for charging events of customers of a specific MSP at stations operated by a particular CPO. In this case, the charging points of the CPO become part of the MSP's network, enabling payment processing for the MSP's customers.

However, due to the large number of CPOs (and MSPs), bilateral roaming agreement may not always be in place. In such a case, a roaming platform provider comes into play, allowing MSPs "to offer their customers to charge their EV at public EV Charging Stations that are not part of the charging network [...] using the same identification [...]" (European Commission, 2019, p. 46).

If neither of these options is available to facilitate payment, the MSP contract of the EV driver may be declined by the CPO, and the customer may need to resort to the less convenient "Ad-Hoc Charging" method.

Pricing

For the different payment methods, the price for the end-customer is influenced by various parties. In case of the "Ad-Hoc Charging", the pricing process starts with the CPO, who is the owner of the charging station. The CPO determines the minimum price based on their internal business case, considering factors such as costs for infrastructure, charging hardware, and electricity expenses. In addition to these costs, a margin is included to compensate the Payment Service Provider (PSP) for handling the payment through a web application or card payment service. The pricing logic and flow of money are illustrated in Figure 9.

(For illustrative purposes, only a kWh-based price scheme is shown as an example. Other tariff schemes, such as those involving singular connection fees, will be briefly discussed in Chapter 6.2.1.)

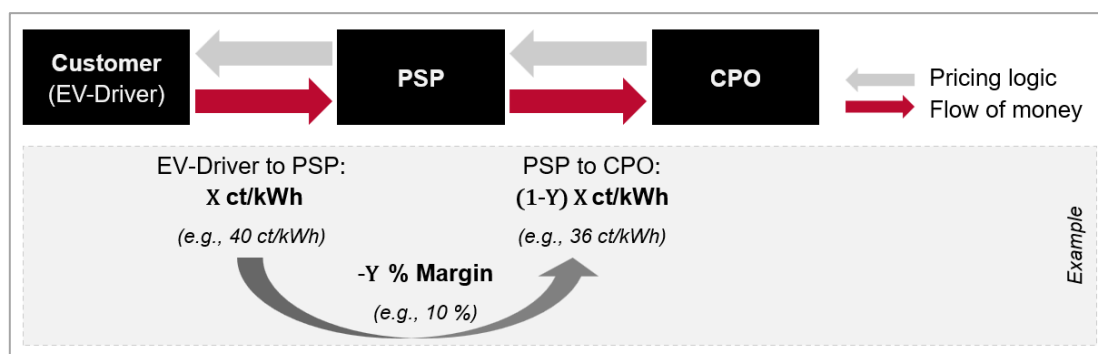


Figure 9 - Pricing mechanism for Ad-Hoc charging (own representation)

In many cases, the price of an "Ad-Hoc" tariff is significantly higher for the EV driver compared to using an MSP. This price difference is inherent to the nature of this payment option. As previously mentioned, "Ad-Hoc Charging" is designed for individual, spontaneous charging events. In such cases, customers do not have a contract with an MSP, and they typically rely

on the specific charging station they are using. These factors give the CPO a strong market position, allowing them to set higher prices.

Different from that are the scenarios that involve an MSP. In these cases, the MSP acts as a representative for a group of potential customers and negotiates charging prices with various CPOs. If a CPO offers excessively high charging prices, they run the risk to be excluded from the MSP network and losing out on a significant number of customers.

In all the cases where an agreement is reached between MSP and CPO, the prices are consolidated, and the MSP provides the EV driver with a uniform pricing structure (see Figure 10).

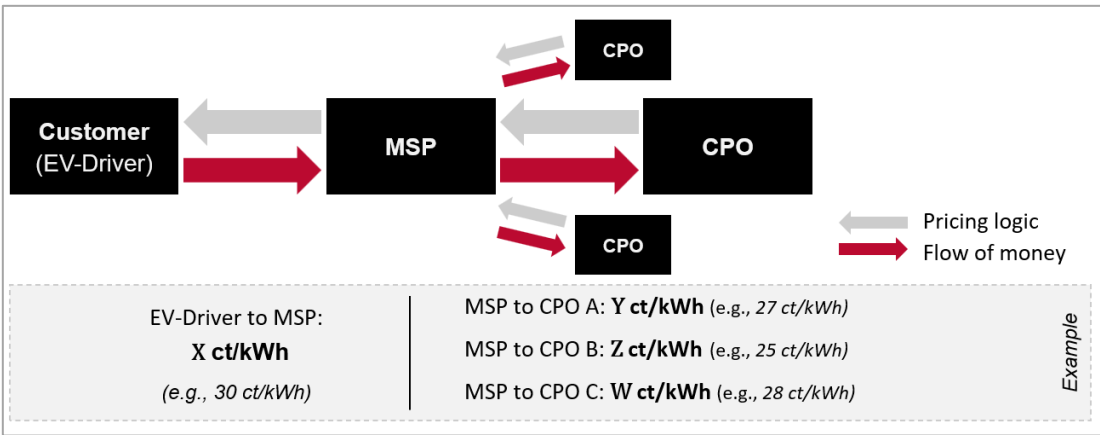


Figure 10 - Pricing mechanism in case of payment via MSP and bilateral roaming agreement (own representation)

Because of the bundling and the complex internal business model of an MSP the price set by a CPO and the price presented to the EV driver are, in a sense, decoupled. This is different from “Ad-Hoc Charging”, where the price set by the CPO is the one directly presented to the customer, only supplemented by a fixed margin of the PSP.

For a configuration where no bilateral roaming agreement between the CPO and MSP exists, an additional party is introduced into the structure (see Figure 11). Particularly for smaller CPOs, the Roaming Platform Provider steps in to handle the bundling and offer a uniform tariff to the MSP. Regional CPOs benefit from this arrangement as their charging points are more likely to be included in a widespread MSP network, making them more attractive to a larger customer base. Similarly, the MSPs benefit from increased CPO coverage within their network.

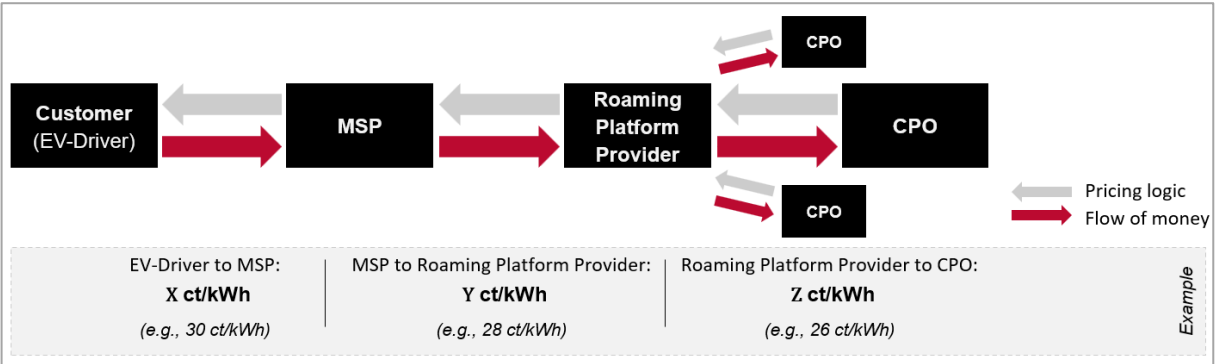


Figure 11 - Pricing mechanism in case of payment via MSP and roaming platform provider (own representation)

For customers, both structures that include an MSP work well and enable fair charging prices. However, the decoupling of customer prices and CPO prices, resulting from the bundling of different tariffs (particularly with roaming platforms), also poses challenges for the charging market, especially when it comes to reversing an upwards price spiral.

It has been observed that this mechanism can prevent disproportionately high prices by excluding specific CPOs. However, it cannot prevent a uniform price increase across the entire sector. This was evident in 2022 when many CPOs and subsequently MSPs had to raise their prices due to increasing electricity costs. The flaw lies not in the inability to prevent upward price spirals affecting the entire sector, but in the inability or significant inertia to reverse that upward trend. This is because the uniform pricing structure prevents CPOs from offering price incentives that may not immediately or directly impact the customer.

For instance, if a CPO is willing to offer lower prices (e.g., coming from the high price levels in 2022), those specific conditions will not be reflected in the mixed calculation of the MSP. As a result, the end-customer will not benefit from these lower prices or even be aware of them, but will remain on the same MSP tariff as before. Only if enough CPOs simultaneously and consistently lower their prices, the MSP tariffs will eventually reflect this trend, leading to a decrease in prices for end-customers (albeit with a delay). However, even in such a scenario, EV drivers will not be able to differentiate between a CPO that quickly adapted and lowered charging prices and one that did so later. It becomes evident that CPOs have no incentive to lower their prices first compared to their direct competitors. Therefore, the only mechanism to mitigate the price level is the risk for individual CPOs of being excluded from various MSP networks if they wait too long and their conditions significantly exceed the market price. This indirect mode of action, stemming from the bundling approach, delays the revision of an upward price spiral compared to a scenario where the price would directly impact the customer.

The understanding of the various payment options, the relationships between the involved parties, and the pricing logic in different scenarios will be crucial for the following discussions, particularly in Chapter 7, where different potentials for improvement will be identified, and specific measures will be recommended and analyzed for their effectiveness.

4 Stakeholder analysis

To optimize outcomes for an operation or organization, it can be helpful to identify stakeholders. These individuals or groups are affected by or can affect the actions, objectives, or policies of the organization. Conducting a structured analysis of stakeholders and their goals can provide valuable insights, enable better anticipation of possible dilemmas, and improve the prospects of success by effectively engaging and managing expectations. Therefore, this chapter will identify all relevant stakeholders for public charging infrastructure and evaluate their goals.

4.1 Commercial Stakeholder

Many stakeholders can be identified based on commercial dependencies. Economic relationships often involve duties and responsibilities that impact at least one of the parties involved. In the context of public charging infrastructure, these stakeholders can be visualized in Figure 8. The EV driver, CPO, and electricity supplier/network operator are directly affected by or have an impact on the operation of a charging station, and they are referred to as primary stakeholders. The following subsections will outline their objectives and interests.

4.1.1 Customer / EV driver

EV drivers have a vested interest in public charging infrastructure as they rely on it to recharge their electric vehicles. The availability and quality of charging infrastructure directly impact EV owners' mobility behavior and routines. Conversely, charging stations depend on EV drivers using them, as charging is their primary function.

The main goal of an EV owner is to charge their vehicle at a public charging station with minimal effort. That includes having convenient and accessible charging options, reliable and efficient charging, and a reasonable cost (financial effort) for the recharged energy. Those wishes can be fractionated and related to the following charging station or process properties:

- **Power:** EV drivers are interested in a charging process that is efficient in terms of both time and energy. They prefer a high charging power that enables a shorter charging time and a greater amount of energy replenished. The desired level of charging power may vary depending on the specific use case (see Figure 3).
- **Price:** The cost of charging an electric vehicle constitutes a significant portion of the vehicle's operational expenses. Therefore, EV drivers aim to minimize these costs and seek affordable charging options.
- **Usability:** Usability encompasses various aspects related to customer satisfaction and convenience. EV drivers desire charging stations that are user-friendly, easily accessible, reliable, and predictable. These factors contribute to enhancing customer comfort and overall satisfaction.

In different use cases, these aspects hold varying levels of importance for EV drivers. Figure 12 shows a qualitative rating of those factors for the four defined use cases or charging locations, public home substitute, public occasional, highway, and work.

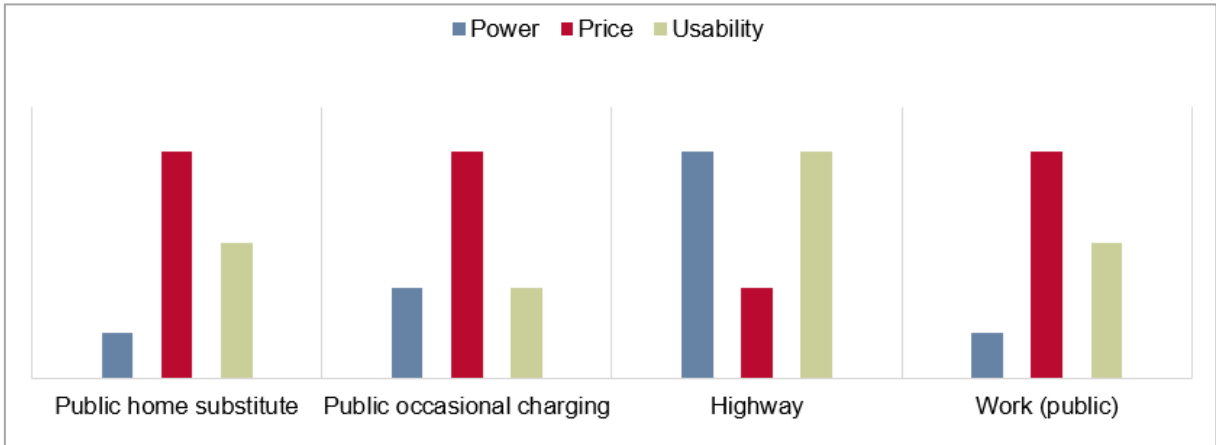


Figure 12 - Importance of different aspects for EV drivers in different use cases (own representation)

Beginning with the charging power, it can be observed that at work or public charging stations used as a home substitute, the expected charging power is relatively low. That is due to the long parking times at these locations. On the other hand, highway charging locations have a high demand for charging power, as discussed in Chapter 2.3.

The importance of pricing levels shows almost the opposite behavior. Locations that are used more frequently for recharging, such as home substitute and work, are associated with higher price sensitivity among customers. The same tendency applies to occasional charging, which is only chosen if it is economically attractive and aligns with other activities.

However, at highway charging stations, the situation is different. Long-distance travels are less frequent for most people, and during such trips, the focus is on charging efficiency (*"I want to charge as much energy in as little time as possible."*) and usability, as there may be limited local alternatives or time constraints. In these scenarios, there is a higher willingness to pay, making the price less important. At other charging locations, where alternatives are available, the dependency on a specific charging location is lower, resulting in lower demands regarding usability.

Chapter 5.4 and 5.5 provide indicators that can measure these aspects more precisely.

4.1.2 Charging station operator

Charging station operators are another stakeholder in public charging infrastructure as they are responsible for building and maintaining the infrastructure.

As a business operation, their main objective is to achieve economic viability and increase revenue, which can be referred to as economic efficiency. To achieve this, they have several secondary goals, such as maximizing the utilization of their charging stations, providing a reliable and convenient service to EV owners, and operating the stations efficiently from an energy perspective. This cascade of stakeholder goals is illustrated in Figure 13. The resulting indicators to track these goals can be found in Chapter 5.1, 5.2, 5.3, and 5.4.

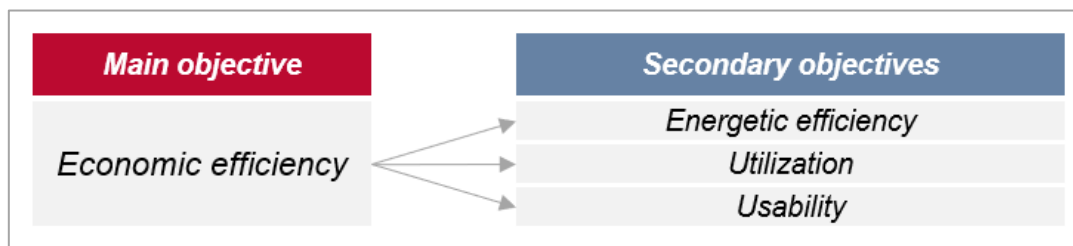


Figure 13 - Stakeholder objectives of charging station operators (own representation)

4.1.3 Grid operator

The grid operators or distribution system operators (DSOs) are stakeholders in public charging infrastructure as they are responsible for supplying the electricity needed to power the charging stations.

Their main objective is to ensure the proper functioning and stability of the grid, especially with the increased adoption of electric vehicles, which may have a significant impact on local capacity requirements, grid congestion, and network stability.

Next to the risk that electric vehicles might pose to the stability of the grid, they can also provide additional flexibility for grid operators. By utilizing smart charging in a vehicle-to-grid (V2G) functionality, the EVs can serve as buffer stations, supplying energy during peak periods, rather than creating additional demand while charging (cf. Helmus and van den Hoed, 2016, p. 736).

Even simpler options, such as demand side management, where charging is adjusted to specific time frames and power levels, for example charging with 3,6 kW instead of 11 kW, can benefit grid capacity.

Overall, DSOs are interested in the predictability of energy demand from charging stations, including the stability of the demand profile and the availability of smart control options to manage that demand effectively.

4.1.4 Secondary commercial stakeholder

In addition to the primary commercial stakeholders mentioned earlier, there are also secondary stakeholders in the public charging sector, such as MSPs, Roaming Hubs, CPO Backend operators, and others. Unlike the primary commercial stakeholders, they are not directly involved with the charging stations themselves. Their objectives are less directly affected as they are only indirectly connected to the charging infrastructure, typically through one of the primary stakeholders.

This is evident in their stakeholder goals as well. Car manufacturers, for example, have a vested interest in public charging infrastructure because it enables them to sell their products. Their primary goal, the sale and adoption of electric vehicles, can be influenced by the availability of charging infrastructure. However, their focus on sufficient charging infrastructure to support the growing demand for electric vehicles is only secondary. Moreover, their interest extends to the broader orientation of the mobility sector and the widespread availability of charging infrastructure in different areas. This stands in contrast to the primary commercial stakeholders who are primarily concerned with the performance of specific charging locations.

Due to the indirect connection to charging infrastructure and the less specific orientation of the goals of these secondary stakeholders, the following analyses will concentrate on the goals of the primary stakeholders only.

4.2 Non-commercial Stakeholder

Next to stakeholders identified through commercial connections, there are additional parties that are involved in or affected by charging infrastructure with objectives that are not primarily economic in nature. One such party is the government, or at a regional level, the municipality.

Governments and municipalities aim to promote sustainable mobility, which includes reducing dependence on fossil fuels, decreasing emissions, and improving air quality. In pursuit of these goals, they actively support the installation of charging infrastructure. Similar to car manufacturers, the government's interest lies not in the performance of specific charging locations, but in addressing the top-level “chicken and egg dilemma”.

It describes the situation where a high volume of BEV is necessary to operate charging infrastructure economically viable, while simultaneously increased adoption of BEV is only reached when with widespread coverage of charging infrastructure.

To overcome this challenge, governments and municipalities establish policies and regulations that encourage the adoption of electric vehicles and the development of charging infrastructure. In cases where municipalities invest in charging infrastructure themselves, their objectives align with those of a CPO as discussed in Chapter 4.1.2.

Another important non-commercial stakeholder group is the residents living in the vicinity of the charging infrastructure. In cases where dedicated charging stations are installed in areas with limited parking spaces, the allocation of parking spots exclusively for electric vehicles can exacerbate parking shortages. This primarily affects residents who do not own electric vehicles and can lead to complaints about municipal incentive programs for electric vehicles, especially when the charging points are underutilized.

These concerns and feedback from residents prompt policymakers to evaluate and adjust the number of charging points in critical areas. They must strike a balance between addressing the space shortage issue raised by residents and ensuring that the charging infrastructure remains accessible and sufficient to meet the needs of electric vehicle users. (cf. Helmus and van den Hoed, 2016, p. 735)

Both, residents and municipalities or the government are not directly involved in the operation of charging infrastructure but have vested interest in its success, similar to the parties mentioned in Chapter 4.1.4. Therefore, they can be categorized as secondary stakeholders as well.

4.3 List of stakeholder objectives

The analyzed stakeholders with their individual objectives are depicted in Figure 14 below. While the list of secondary commercial stakeholders may not be exhaustive, it is argued that all primary stakeholders are included with their objectives. These primary stakeholders cover the parameters that determine the main area of conflict for public charging infrastructure and to some extent the interests of the secondary stakeholders.

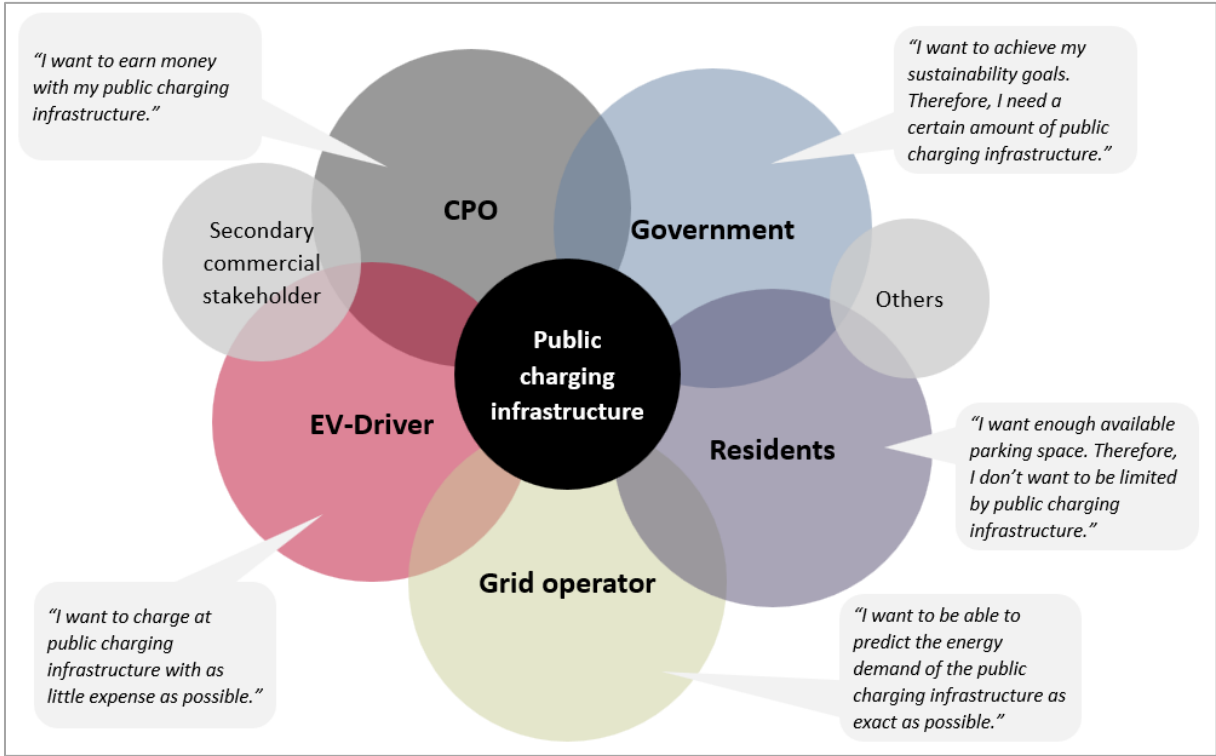


Figure 14 - Stakeholder objectives and area of conflict for public charging infrastructure (own representation)

5 Identification and analysis of key performance indicators

A key performance indicator (KPI) is a measurable value that demonstrates how effectively an organization or individual is achieving specific objectives or goals. KPIs are used to evaluate performance over time and to identify areas that require improvement. They can be applied to various aspects of a business or project, including financial performance, customer satisfaction, employee productivity, website traffic, and more. The following chapter will define the necessary KPIs to quantify the performance of public charging infrastructure with several stakeholder goals deduced in the chapter before. The defined set of KPIs will then serve as a main instrument for a uniform and comprehensive analysis of public charging infrastructure.

5.1 Economic Efficiency

The upcoming chapter will provide general information about the KPI of economic efficiency. Additionally, it will offer an overview of how this KPI is calculated and provide insights into its limitations.

General

The KPI of *economic efficiency* measures how effectively an organization utilizes its resources to generate revenue or profit. It reflects the ability of a business to minimize costs while maximizing revenue, and it is a crucial metric for evaluating the financial performance of a company. For public charging infrastructure the primary business interest lies with the CPO, as discussed in Chapter 4.1.2.

Calculating this KPI involves various options, such as the return on investment (ROI), net profit margin, or gross profit margin. These ratios measure the profitability of a company in relation to the resources invested, such as the capital, labor, and materials.

A high economic efficiency indicates that a business is generating significant revenue or profit while minimizing costs, which is desirable. Conversely, a low economic efficiency suggests inefficient resource utilization, prompting the need for cost reduction or revenue improvement initiatives.

While these analyses can be applied to the overall business of a charging point operator (CPO), targeted and specific analyses are essential to identify actionable measures for improving economic efficiency. For instance, a top-level analysis may reveal high overall expenses, but a detailed analysis could pinpoint specific high-power chargers with low utilization as the primary contributors. By conducting charge point-level analyses, CPOs can accurately target and address problematic areas rather than implementing generalized measures.

The importance of specific economic analyses at the charge point level holds true across various cases, as discussed in Chapter 7. Therefore, CPOs operating multiple charging stations

in different locations should analyze each charging point as a distinct profit center or consider defined groups of charging points for more effective identification of improvement opportunities.

Calculation

For evaluating the economic efficiency of public charging infrastructure, the profit margin serves as a suitable indicator. It can be calculated by comparing the benefits and costs associated with each charging point or group. Figure 15 outlines the key elements involved in this analysis.

To be able to compare all the listed values, it is necessary to find a common denominator or unit. Running or operational costs, such as electricity purchases, will be combined with depreciation of charging equipment or infrastructure, which is based on the initial investment cost and the expected lifetime.

To ensure optimal operation, it is essential to conduct these analyses regularly. Monthly or weekly updates provide the opportunity to respond to performance changes promptly. It has been observed in practice that conducting yearly analyses yields similar potential for improvement, but with a greater time delay that may result in a loss of earnings.

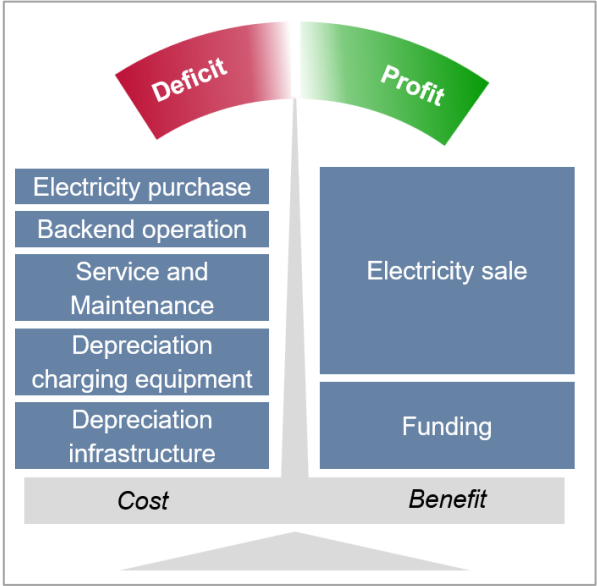


Figure 15 - Costs and benefits of charge points (own representation)

While costs related to static factors, such as initial investments, remain unchanged in monthly or weekly economic assessments of a specific charging point, they still need to be considered to obtain a comprehensive overview. More dynamic or operational costs like service or maintenance will be added to them.

For the same accounting period, the revenues generated by the charging point, including electricity sales or potential funding, will be calculated. These revenues are then compared to the expenses incurred to determine the profit margin (see Equation 5.1).

$$\text{Profit Margin} = \frac{\text{Net Income}}{\text{Revenue}} = \frac{\text{Revenue} - \text{Expenses}}{\text{Revenue}} \quad \text{Revenue and expenses in } \text{€/CP per week/month/year} \quad (5.1)$$

The application of the before described procedure can be seen in Chapter 6.2.

Limitation of the KPI definition

When calculating “net profit margin” as an economic ratio, it is important to take taxes and costs for interest payments into account. However, since economic efficiency is only one of several KPIs for public charging infrastructure, the calculation has been kept simple at this stage.

Additionally, it is important to note that economic efficiency is not the only KPI that can be considered when evaluating a business's financial performance. Other KPIs, such as liquidity, solvency, and growth potential, are also important for gaining a comprehensive understanding of a business's financial health. In this analysis they were also omitted due to simplification reasons.

5.2 Energetic Efficiency

The following chapter provides an overview of the KPI of energetic efficiency, including its significance, calculation methods, and inherent limitations.

General

The KPI of *energetic efficiency* is commonly utilized in the context of resource management to assess the effectiveness of energy usage within an organization. It quantifies the amount of energy used per unit of production or per square foot of building space. The specific formula for calculating energy efficiency may vary depending on the context but typically involves comparing energy consumption to output or activity achieved. Improving energy efficiency can assist organizations in reducing energy consumption, lower their carbon footprint, and saving money on energy costs.

In the case of public infrastructure, the output or benefit of the charging system is the energy transferred to electric vehicles. The boundary for the analyzed system, “charging infrastructure”, is the connector that is plugged into the car. This is important because losses may occur in the car's system itself, which can be influenced by factors such as battery technology or battery size.

Therefore, when discussing the efficiency of charging infrastructure, these car-related losses should not be considered. The input or cost is the energy required by the infrastructure. Consequently, in this specific case, the energy consumption and the related output have the same dimension or unit.

Calculation

To calculate the energetic efficiency, the ratio of cost and benefit is utilized (see Equation 5.2).

$$\begin{aligned} \text{Efficiency} &= \frac{\text{benefit}}{\text{cost}} = \frac{E_{\text{out}}}{E_{\text{in}}} = \frac{E_{\text{out}}}{E_{\text{process}} + E_{\text{idle}}} \\ &= \frac{E_{\text{out}}}{\frac{E_{\text{out}}}{\eta_{\text{process}}} + \int P_{\text{idle}}} \end{aligned}$$

E_{out}: Electrical energy transferred from the charging infrastructure to the car

E_{in}: Total electrical energy demand of the charging infrastructure

E_{process}: Electrical Energy used during the charging process

E_{idle}: Electrical energy used in idle state

η_{process}: charging efficiency of the charging infrastructure

P_{idle}: idle power of the charging infrastructure

(5.2)

The difference between the two quantities – benefit and cost – is affected by two factors.

The first factor is the charging efficiency of the infrastructure during an active charging process (η_{process}). Typical values for AC charging stations as well as HPC technology exceed 95 %. However, it is important to note that this does not include losses on the vehicle side.

The second factor that impacts the overall energy demand of the charging infrastructure is the idle power (P_{idle}). While AC charger typically have a power demand ranging between zero and ten watts during standby state, whereas HPC chargers can have significantly higher consumption.

There are several reasons for this disparity. Firstly, the altered use case for HPC technology often results in stations being equipped with big LED screens (unlike AC charging stations) to display a variety of information or advertising.

Additionally, the ability to transfer electricity at high power levels necessitates a more robust electrical design, which leads to higher idle power consumption.

Lastly, depending on the specific system configuration, HPC technology is always connected to “upstream” energy consumption for converters and other power electronics. (The same is applicable for AC technology but with another ratio and therefore the upstream energy losses have less influence). When combined, the idle power demand of an HPC station can reach low single-digit kilowatts.

The application of the procedure described above can be observed in Chapter 6.3.

Limitation of the KPI definition

In general, it is possible to examine idle power and charging efficiency separately, but for the purpose of this work, the KPI combines both charging and standby losses. This aggregation provides a well-rounded understanding, although in certain cases, a separate analysis may be necessary.

Another challenge lies in establishing the correct boundary for the charging system. In terms of the car, the connector determines the point at which electrical energy is delivered. However,

defining the entry point for electrical energy in the "upstream" system (such as converters, power electronics, etc.) can be more complex, especially when the converter serves multiple purposes beyond supplying the charging station. One possible solution could be aligning with the electricity cost structure of the system.

The final limitation arises when considering the perspective of the customer. Customers are primarily interested in the energy that is transferred to the car and available for their mobility needs. Therefore, from their standpoint, the energy transfer does not conclude at the charging connector. The losses related to the charging system of the car (converter, battery management system, battery, etc.) affect the actual amount of energy that is usable for mobility. However, these losses are not considered when calculating the energy efficiency of the charging infrastructure.

5.3 Utilization

The following chapter delves into the KPI of utilization, examining its importance in performance evaluation and exploring different calculation methodologies. Additionally, a critical analysis of the limitations associated with this indicator is presented.

General

The KPI *utilization* is a metric used to assess the efficiency of resource utilization in achieving organizational objectives. It quantifies the extent to which specific assets or resources are being utilized, enabling organizations to identify any underutilized resources and optimize their usage. By doing so, organizations can enhance their overall performance and profitability while also promoting sustainability by reducing resource consumption and minimizing environmental impact.

Calculation

For public charging infrastructure, there are two methods commonly applied to calculate utilization. The first method is asset utilization, which measures the percentage of time that an asset or resource is being used out of the total available time.

For example, if a charging station is occupied with an ongoing charging process for six hours a day, the asset utilization would be 25 % (see Equation 5.3). It is important to consider the charging station's opening hours when determining the total available time for calculation.

$$\text{Asset Utilization} = \frac{\text{Charging Time}}{\text{Business Hours}} \tag{5.3}$$

| | | | |
|----------|--|------|--|
| Example: | Time being used (Charging Time): | 6 h | Asset Utilization = $\frac{6 \text{ h}}{24 \text{ h}} = 25 \%$ |
| | Total available time (Business Hours): | 24 h | |

Another option is to compare the actual output generated by the specific resource to its maximum capacity or output. For example, if a charging point has an installed power of 22 kW and transfers 100 kWh of energy within a 24-hour period, the capacity or energetic utilization would be approximately 19 % (see Equation 5.4). This metric shows the average amount of the maximum possible power output that was utilized.

$$\text{Capacity Utilization} = \frac{\text{Charged Energy}}{\text{Maximum Output}} \quad (5.4)$$

Example: Realized Output (Charged Energy): 100 kWh
 Maximum Output: 24 h × 22 kW = 528 kWh Capacity Utilization = $\frac{100 \text{ kWh}}{528 \text{ kWh}} \approx 19 \%$

The application of the procedure described above and a classification of utilization rates for different types of public charging infrastructure can be found in Chapter 6.4.

Limitation of the KPI definition

It is important to note that the energetic utilization is not solely depending on the performance of the charging infrastructure but also on the car and especially its charging curve. In some cases, the car limits the charging power to protect its battery, which is then lower than the maximum output power of the charging infrastructure. Therefore, not every indication that is derived from the KPI can be improved with solely the charging hardware. The other components of the charging system, such as the BEV itself, need to be considered when analyzing the KPI.

This also affects the comparability of results for AC and HP charging points. Due to their different power levels and use cases, it is challenging to directly compare them under the KPI utilization (see Chapter 6.4).

Furthermore, both asset and capacity utilization are significantly influenced by downtime periods of the hardware. During these periods, no charging processes can take place, and no energy can be transferred. It is crucial to consider these downtime periods in the analysis process to avoid treating charging points with generally low utilization in the same way as those with frequent downtime. In some cases, it may be beneficial to exclude downtime or maintenance periods from the assessment.

5.4 Usability

The upcoming chapter will provide general information about the KPI of usability. Additionally, it will offer an overview of how this KPI is calculated and assess potential limitations.

General

The KPI usability quantifies how easy and effective a user interaction with a particular system or product is carried out. It measures the extent to which a system or interface meets the needs

and expectations of its users, allowing organizations to identify areas for improvement and optimize user experience. From the various ways to calculate the KPI, the “task completion rate” seems applicable to the charging use case and advantageous from a CPO’s point of view, since it is relatively easy to establish. The described rate measures the percentage of users who are able to successfully complete a specific task or set of tasks within a product or system. It helps to identify areas where users may be struggling or where the design of the product or system may be causing confusion or errors.

For public charging infrastructure the task to be completed is a successful charging process (including the payment process). By monitoring and improving the success rate of charging processes, the CPO can enhance the overall user experience, increase user satisfaction, and drive adoption and engagement with their systems. This, in turn, can positively impact the organization’s performance, profitability, reputation, and customer loyalty.

Calculation

For this KPI (as for others) the specific configuration or calculation depends on the availability of data. A sophisticated theoretic definition of a KPI cannot generate any benefit in practice if the needed data is not available. Considering that, the simplest definition from a CPO’s point of view with access to a CPO backend is the technical usability. As depicted in Equation 5.5, the share between technically successful and total charging processes is calculated.

$$\begin{aligned}
 \text{Technical Usability} &= \frac{CP_{\text{success}}}{CP_{\text{total}}} & \text{CP}_{\text{success}}: & \text{number of successful charging processes} \\
 &= \frac{CP_{\text{total}} - CP_{\text{technically flawed}}}{CP_{\text{total}}} & \text{CP}_{\text{total}}: & \text{total number of charging attempts} \\
 & & \text{CP}_{\text{technically flawed}}: & \text{number of technically flawed} \\
 & & & \text{charging processes}
 \end{aligned}
 \tag{5.5}$$

The criterion used to differentiate between successful and flawed charging interactions from a technical standpoint can be established in various ways. The primary objective of identifying unintentional charging interruptions or breakoffs can be accomplished by examining either the charging time or the amount of recharged energy. For instance, any charging process with a duration shorter than two minutes could be considered unsuccessful based on the first criterion. In the case of the second criterion, charging processes involving less than one kWh of energy could be deemed flawed. The application of the described procedure and the impact of different criteria and their adjustments are presented in Chapter 6.5.

In addition to the technical aspect of energy transfer, most charging sessions also involve monetary transactions. Similar to the technical component, errors can occur during the payment process. For specific evaluations, the definition of a successful charging process can also encompass the payment aspect. The corresponding definition of usability is provided below (see Equation 5.6).

$$\begin{aligned} \text{Extensive Usability} &= \frac{CP_{\text{success}}}{CP_{\text{total}}} & \mathbf{CP_{\text{success}}:} & \text{number of successful charging processes} \\ &= \frac{CP_{\text{total}} - CP_{\text{flawed}}}{CP_{\text{total}}} & \mathbf{CP_{\text{total}}:} & \text{total number of charging attempts} \\ & & \mathbf{CP_{\text{flawed}}:} & \text{number of charging processes with technical or payment errors} \end{aligned} \tag{5.6}$$

The classification of charging processes with successful payments is done by the CPO backend or derived from it. A flawed process could appear for example if no payment information could be identified, or faulty measuring values prevent accurate billing.

Limitation of the KPI definition

The share between successful and flawed charging processes does not consider the total amount of charging events, which poses two problems. Firstly, evaluations for charging points with low utilization and a small random sample may not be representative. One possible solution is to mark evaluations with insufficient database as unreliable. This issue will be given specific attention during the practical application of the KPI in Chapter 6.5.

The second challenge is that system downtime, where no charging attempts can be recorded, does not affect the previously defined usability ratios. To address this, a possible solution is to expand the KPI set and include the downtime of the charging infrastructure as its own KPI. The benefit or need for that will be discussed in Chapter 8.

Next to the before mentioned limitations, it is important to note that not all problems appearing at a charging station are directly connected to unsuccessful charging processes (“hard errors”). Issues such as customer concerns about delays in starting the charging process or lack of information about its progression can be considered “soft errors”. These soft errors may not result in an unsuccessful charging process and therefore cannot be detected by the CPO through their backends. However, they still impact the customer's charging experience and should be a concern for CPOs. To address these soft factors, the KPI of user-friendliness, as described in Chapter 5.5, was developed.

5.5 User-friendliness

The following chapter provides an overview of the KPI of user-friendliness, including its significance, an evaluation scheme, and inherent limitations.

General

The KPI of user-friendliness, similar to the KPI of usability, measures how easy it is for users to interact with a product or service. However, unlike the explicit evaluation of task completion rate, the user-friendliness KPI considers less discrete aspects such as user satisfaction.

To assess user-friendliness and gather knowledge in this area, a company can employ a combination of qualitative and quantitative methods. Examples for those are usability testing, surveys, and customer feedback. Each approach has the goal to identify areas where users may

encounter difficulties or experience frustration when using a product or service. Subsequently, improvements are made to address these issues.

The specific configuration of the user-friendliness KPI depends greatly on the chosen evaluation method. However, certain aspects are important and should be considered regardless of the method used to evaluate user-friendliness in public charging infrastructure. Therefore, this thesis will provide a list of these aspects as a guideline for CPOs to assess user-friendliness in advance and derive initial indications. This list can also serve as a foundation for further examinations, such as usability testing or customer surveys.

This approach is particularly favorable considering that the effort and financial investment required for methods like surveys go beyond the scope of this thesis.

Evaluation scheme

Since the potential influences on the user experience during a charging process are virtually limitless, a prioritization of aspects had to be conducted. In this step, the work of the joint research project “Wirkkette Laden” (charging process chain) funded by the Federal Ministry of Digitalization and Transport was consulted.

The project concentrated on issues that hinder reliable and unobstructed charging events, utilizing both real-world data and data from participant trials. A six-month study involving over 60 EV drivers with different vehicle types was carried out to document their experiences with charging events at various locations. The identified errors were analyzed, and the data logging of the project partners involved was examined to determine the root causes of these issues (cf. NOW GmbH, 2023).

As a result, “twelve design recommendations for public charging infrastructure” were derived. These recommendations specifically address and improve aspects that are currently problematic in terms of the reliability of charging events, making them highly suitable as the foundation for the “user-friendliness listing”. To complete the proposal, additional aspects from the categories of charging location and station design, such as detectability and signage, integration with other services, as well as safety and comfort considerations, were included.

Inspired by the “twelve design recommendations”, this proposal categorizes the aspects that influence the user-friendliness of a charging station into mandatory and optional features. Furthermore, aspects related to the charging station itself, the parking space, and the surrounding infrastructure are separated.

Table 5-1 - Obligatory aspects for user-friendliness of charging stations

| Obligatory aspects | | Source |
|-------------------------|---|---|
| Charging station design | 1. Consistency in the use of EVSE-ID for the identification of the charging connectors. | (cf. Wirkkette Laden Verbundprojekt et al., 2023) |
| | 2. Careful placement of EVSE-ID to preclude mix-ups. | |
| | 3. Easy identification and readability of controls (like touchscreens on the charging station) with no influence of different weather conditions. | |
| | 4. Standardization of URLs related to the QR codes which are attached to the charging station, so they are readable by any app. | |
| | 5. Instruction of all possible ways for authentication on the charging station. | |
| | 6. High visibility of the service hotline of the CPO on the charging station. | |
| Charging location | 7. Good detectability and clear signage towards and on the charging station (including available charging power). | - |

Table 5-2 - Optional aspects for user-friendliness of charging stations

| Optional aspects | | |
|-------------------------|--|---|
| Charging station design | Payment | |
| | 8. Acceptance of various forms of payment. | |
| | 9. Transparent pricing, with display of price per kWh before charging and overall cost after charging. (cf. Wirkkette Laden Verbundprojekt et al., 2023) | |
| | Information and Connectivity | 10. Provision of feedback to the customer on the charging process and its action steps. (cf. Wirkkette Laden Verbundprojekt et al., 2023) |
| | | 11. Implementation of a user-experience concept to facilitate intuitive and easy usability. (cf. Wirkkette Laden Verbundprojekt et al., 2023) |
| | | 12. Compatibility with mobile apps and navigation systems. |
| | | 13. Availability of option for direct user-feedback on the charging station. |
| | Safety | 14. Implementation of safety and security measures to protect users and their vehicles. |
| | | 15. Equipping of charging location with good lighting. |
| | | 16. Mechanisms for a quick and customized maintenance. |
| | Fail-safety | 17. Provision of more than one connector at the charging location. |
| | | 18. Covering of/Compatibility with different connector types. |
| | Comfort | 19. Neat appearance of the charging station and implementation of a cleaning concept. |
| | | 20. Provision of weather protection at the charging station. (cf. Wirkkette Laden Verbundprojekt et al., 2023) |
| | | 21. Easy cable handling at the charging station. |
| | | 22. Reservation of parking spots for BEV only and/or availability of reservation for specific charging time slots. |
| | Charging location | 23. Barrier-free parking space and easy maneuvering in and out of the parking lot. |
| | | 24. Integration of renewable energies at the charging location. |
| | | 25. Consideration of the overall environmental impact of the charging infrastructure, including the use of sustainable materials, during the design and setup of the charging location. |
| | | 26. Integration with other services (like restaurants, shops, or restrooms). |

The obligatory aspects can be regarded as minimal requirements, while optional aspects are suggestions that would enhance the user-friendliness if considered but are not essential in every use case. For a better comprehension, an application, as well as an interpretation of the user-friendliness KPI can be seen in Chapter 6.6.

Limitation of the KPI definition

As mentioned before, there are various influences on the user experience during a charging process. Therefore, it should be mentioned that a KPI in this category can only indicate problems within the listed categories. Despite careful selection of categories, there may be out-of-scope issues that arise at specific charging locations. Sometimes these issues are difficult to identify in advance, which is why direct customer feedback is invaluable. However, implementing methods like customer feedback or conducting surveys requires significant effort and financial resources, which may result in this general set of rules remaining unchanged. This is how possible blind spots could stay unrecognized.

In specific cases, it can be helpful to adapt the KPI set. As mentioned before, customer use cases and needs can vary greatly across different charging locations (refer to Chapter 2.3 and 4.1.1). Therefore, it could be beneficial to assign different weights to factors and, for example, place more emphasis on the integration with other services like restrooms at highway charging hubs compared to regular public charging stations.

Furthermore, all the aspects were considered from a local perspective, which is appropriate since CPOs apply them to specific charging locations they own. However, some factors can also provide information beyond this localized analysis when considered from a global or macroscopic perspective. For instance, the parking situation was evaluated locally to assess the design of the parking lot. In a broader approach, the placement of the charging location in an urban area and its relation to the charging and mobility behavior of EV drivers could be evaluated. This would change the question from “Is the charging location well designed?” to “Is the charging location well placed and suitable for people’s mobility behavior?”.

However, conducting this kind of assessment would encounter different challenges. Firstly, it would require a higher amount of data, which may not be as readily accessible or collectible as in a local analysis. Secondly, even if the assessment yielded valuable insights, feasibility could be limited due to constraints such as the availability of alternative parking lots or planning permissions for charging infrastructure.

The same considerations apply to aspects that influence the charging experience of EV drivers but are influenced by more than one party. The “Wirkkette Laden” joint research project found that 44 % of errors were caused by the charging infrastructure, which falls solely under the responsibility of the CPO (cf. NOW GmbH, 2023). Conversely, this means that 56 % of the problems were triggered by other factors, such as interfaces or gateways between the CPO

and MSP backend, or an app provided by a car manufacturer and its corresponding backend. Identifying these errors in the first step is challenging and resolving them in the second step is even more difficult. That is why the user-friendliness aspects of the KPI primarily focus on the charging station itself and elements that solely lie within the responsibility of the CPO.

Addressing other problems involving multiple parties requires an overarching approach or standardization. This is beyond the scope of a single CPO and would be wrongly contextualized within this KPI framework.

5.6 Predictability

The following chapter briefly comments the KPI of predictability, offering an evaluation scheme and exploring different limitations associated with this indicator.

General

Predictability is a KPI for grid operators or DSO because it enables them to manage and plan the electricity grid efficiently and effectively. In the context of public charging infrastructure, predictability refers to the ability to accurately project the electricity demand from electric vehicles charging within a specific grid area.

Next to private charging infrastructure, whose installation is already reportable, public charging stations with their high power and energy demand have a significant impact. For instance, if the demand exceeds expectations, it can strain the electricity grid and potentially result in power outages. Conversely, if the actual demand is consistently lower than anticipated, it can lead to unused capacity and increased costs.

Evaluation scheme

The benefit of having a charging infrastructure-related predictability key performance indicator (KPI) is that it enables discussions about when further investments in the grid are needed to ensure grid quality. The grid operators are responsible for this, and they gather insights from two factors: “peak power level” and “peak shaving potential”.

The primary factor, peak power level, is significant because it determines the occurrence of power outages. If the peak power demand exceeds the grid capacity, power outages are more likely to happen at the neighborhood level. To prevent such scenarios, it is advisable to minimize peak power demands whenever possible. (cf. Helmus and van den Hoed, 2016, p. 739)

The second criterion, peak shaving potential, provides information about the system's flexibility, which allows for solutions in cases of capacity shortage. In the context of charging stations, this could involve delayed charging or charging with variable capacity. To alleviate pressure on the grid during peak hours, charging processes could be delayed, or charging stations could operate with lower capacity. (cf. Helmus and van den Hoed, 2016, p. 739)

In addition to, or instead of, considering the peak shaving potential, the percentage of charging points with smart charging capabilities could be evaluated.

The application of this KPI and a practical evaluation of public charging infrastructure can be found in Chapter 6.7.

Limitation of the KPI definition

One possible limitation of this KPI is that the capability of the charging station does not automatically apply to the connected car. In the case of new smart charging technology, this could mean that the communication protocol or the hardware of the connected car may not be as advanced as the charging station, thereby preventing smart charging. The hardware requirements on the vehicle side and the need for high-level communication between the infrastructure and the car pose challenges and risks that are not reflected in the KPI.

Additionally, as potential consequences for customer acceptance of smart charging at public charging stations in cases of unsatisfactory or failed charging events are not addressed by the KPI.

5.7 List of KPIs

A concise list of the identified KPIs, along with their defined evaluation scheme or calculation method and the relevant stakeholders, can be found in Table 5-3. This collection of indicators will serve as the framework for the exemplary analysis of existing public charging infrastructure.

Table 5-3 - KPI overview for public charging infrastructure

| KPI | Calculation / Evaluation | Unit | Primary Stakeholder | Secondary Stakeholder |
|-----------------------------|--|--------|---------------------|-----------------------|
| Economic Efficiency | Profit Margin | % | CPO | - |
| Energetic Efficiency | Energy Efficiency | % | CPO | - |
| Utilization | Asset Utilization | % | CPO | - |
| | Capacity Utilization | % | | |
| Usability | Technical Usability | % | CPO | EV driver |
| | Extensive Usability | % | | |
| User-friendliness | List with obligatory and optional design recommendations | Index | EV driver | CPO |
| Predictability | Peak power level | kW | Grid operator | - |
| | Peak shaving potential (or % of charging point with smart charging capability) | kW (%) | | |

6 Analysis of existing public charging infrastructure at AUDI AG headquarters and application of KPIs

In this chapter, the focus will be on analyzing existing and operating public charging infrastructure. The previously defined set of KPIs will be the basis and framework for this breakdown. The aim is to examine the practicality of these indices and identify any potential need for adaptation.

The application of these KPIs will be demonstrated using the charging infrastructure established and operated by AUDI AG. However, it is necessary to define a system boundary for the specific charging location and operation. This will determine what will be considered or excluded in the subsequent steps.

Following the definition of the system boundary, a general analysis of the identified system will be conducted (see Chapter 6.1) before delving into the analyses related to the performance indicators in Chapters 6.2 to 6.7.

6.1 Charging ecosystem at AUDI AG

CPO

AUDI AG is a German automotive company with its headquarters in Ingolstadt, Germany. Audi belongs to the premium car segment and is known for its advanced technologies in cars, such as all-wheel drive or virtual cockpits. Their product portfolio includes cars with combustion engines, as well as hybrid, or electric powertrains.

The company has a global network of production facilities and sales entities, spread across Europe, Asia, North America, South America, Africa, and Oceania. Audi's major markets comprise countries such as China, the United States, or the European Union.

As a subsidiary of the Volkswagen (VW) Group, Audi follows a clear strategy of promoting sustainable mobility solutions through electrification of their powertrains. For that reason, Audi is investing in battery technologies as well as in charging infrastructure, where they formed partnerships with other companies to expand the network of charging stations.

On a local level, Audi not only invests in charging infrastructure but also operates it as a CPO with various objectives. These range from providing necessary charging facilities for the development of new electric vehicles (*process charging*) to offering charging solutions for employees (*charge at work*).

Charging station

In general, AUDI AG operates over 2,000 charging points, with the majority located in and around its headquarters in Ingolstadt. These charging points serve different purposes and can be categorized as process charging, internal charging, and external or public charging.

-
- **Process Charging:** These charging infrastructures are used for development or production processes. They may consist of established or new types of charging infrastructure, depending on demand, and are mainly installed within the company grounds. Since they serve specific purposes, they are not open for arbitrary or public use.
 - **Internal Charging:** These charging stations are installed within the company premises and are available for any electric vehicle allowed on the premises. They can be used by utility or department vehicles or by BEVs driven by high-ranking managers of the company. These charging stations can be considered semi-public, as they are meant for regular or conventional use, but only for defined groups of people with limited access. They are not open to the general public.
 - **External Charging:** These charging stations are located outside but close to the company grounds and are designated for employees (or customers) with electric vehicles. They do not have any access restrictions and can be compared to conventional public charging locations.

For the following analyses, only the external charging points around the Audi headquarters in Ingolstadt will be considered due to their transferability of findings to other public charging infrastructures. The reference date for all data exports reflecting the year 2022 was chosen as 18.01.2023. For more recent analyses evaluating single months, other reference dates were selected. It's important to note that due to the ongoing expansion of charging stations, small differences, such as the total number of evaluated charging points, may appear.

As of 18.01.2023, the clearly defined subgroup (external charging points located in Ingolstadt and operated by AUDI AG) consists of over 480 charging points in total. Approximately 98 % (471) of these charging points utilize AC technology with a maximum power of ≤ 22 kW, while the remaining 2 % (10) use HPC technology with maximum charging powers ranging from 150 to 350 kW.

In theory, all of these chargers provide a combined maximum charging power of 12,800 kW, with around 10,350 kW on alternating current and 2,450 kW on direct current. However, the maximum installed charging power is a theoretical value because the actual current supply also depends on other infrastructure factors, such as transformers designed with smaller simultaneity factors (usually around 0.33 for AC charging infrastructure). These factors limit the potential power output.

EV driver / Customer

As previously mentioned, the investigated charging stations are not limited to a specific group of people and are open to the public. However, due to their placement around the company

grounds, such as parking lots or decks, the majority of users are employees. This can be observed in Figure 16, which illustrates the starting times for charging events throughout the week. For AC charging infrastructure the majority of charging events starts between 5:00 and 8:00 in the morning. That coincides with the start of the production morning shift as well as the beginning of labor for most office workers. Accordingly, a high preference towards the working week (Monday to Friday) can be seen with AC chargers. Further analysis reveals that the average AC charging event at work lasts 7.5 hours, during which an average of 27.8 kWh is transferred to the car.

A closer examination of the HPC charging points reveals that they are not primarily influenced by the “charge at work” use case. The starting times of charging events for HPC chargers are evenly distributed throughout the day, ranging from 5:00 to 20:00. Additional analyses indicate that the average duration of a DC charging event is approximately 31 minutes, with an energy transfer of 36.3 kWh.

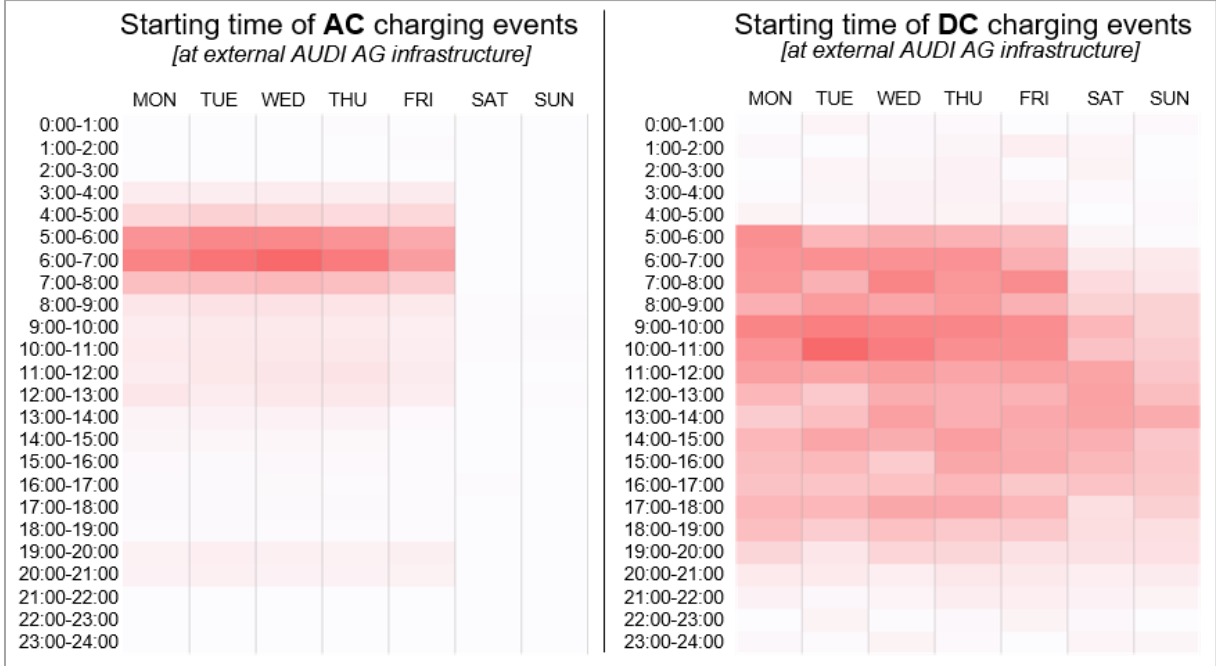


Figure 16 - Starting times for AC and DC charging events at external AUDI AG infrastructure (own representation)

Regarding the AC charging stations, the clear tendency towards the "charge at work" use case is neither negative nor positive in itself. From the perspective of the Charging Point Operator (CPO), AUDI AG, it is actually an anticipated and desired phenomenon. The establishment of external charging infrastructure aligns with their goal of providing consistent and attractive solutions for their employees. On one hand, offering charging facilities emphasizes the practicality of electric mobility for daily use, which is important for the company's electric mobility strategy. On the other hand, it provides convenience for employees who already own a BEV.

Given this context, it is important to differentiate between AC and HPC infrastructure in the following analyses, as well as recognize the dominance of the "charge at work" use case for

AC chargers. It should be noted that the proposed actions for improvement in Chapter 7 may have some limitations in terms of their transferability to other public charging infrastructure. For instance, the consideration of weekdays would typically encompass Monday to Friday for "charge at work" infrastructure, but Monday to Sunday for other public infrastructure.

Roaming Platform / MSP / Ad-hoc charging

As AUDI AG operates on a relatively small scale as a CPO, they have few direct or bilateral roaming agreements with MSPs. As explained in Chapter 3.3, most of the required roaming agreements to enable customer payment with various MSPs are facilitated through a roaming hub. Currently, Audi is part of the roaming hub provided by chargecloud GmbH. This hub serves as the gateway where charging price updates and conditions from both MSPs and CPOs are synchronized.

The connections within this ecosystem are illustrated in Figure 17, which represents an adapted version of the general public charging sector (Figure 8, Chapter 3.1) specifically focusing on the external Audi charging infrastructure. Additionally, the Ad-hoc charging option, where EV drivers and AUDI AG as a CPO can directly interact, is also included as a mandatory payment option.

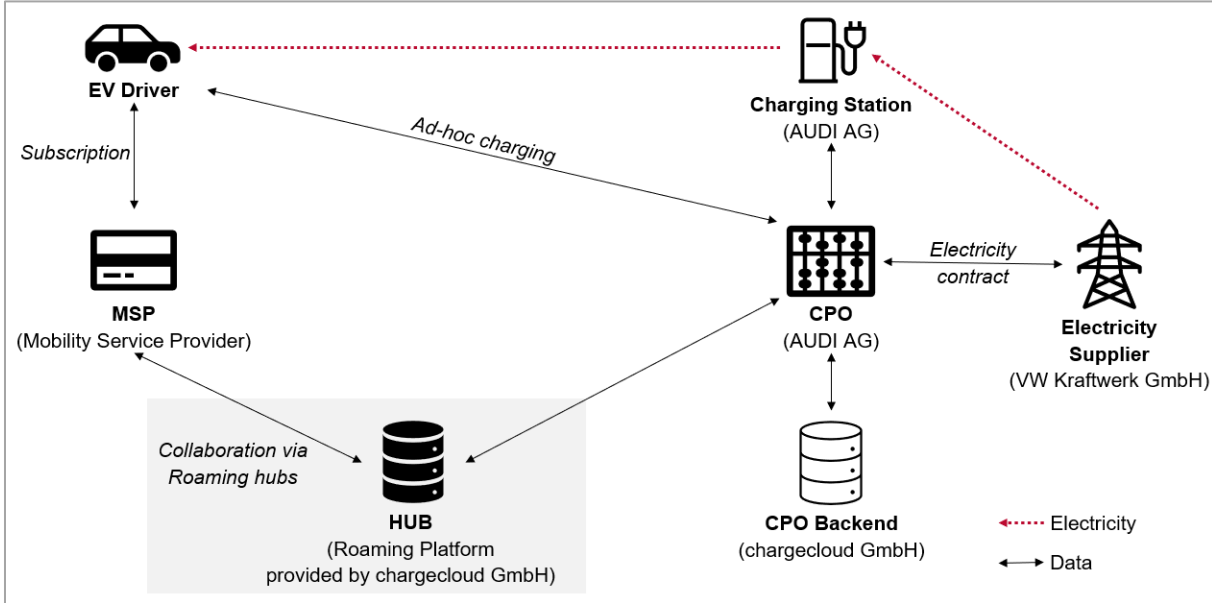


Figure 17 - Structure of the ecosystem for public AUDI AG charging infrastructure (own representation)

Electricity Supplier

The electricity supplier for Audi owned and operated charging infrastructure depends on the location of the facility. In most of the cases, the infrastructure is supplied by the factory’s electricity grid , with the electricity supplier being “VW Kraftwerk GmbH”. However, for specific parking lots, the electricity is supplied by “Stadtwerke Ingolstadt GmbH”. This configuration can lead to slight variations in the electricity purchase price across different locations.

6.2 Analysis regarding the economic efficiency

This chapter aims to analyze the economic performance of the Audi-owned public charging infrastructure. As outlined in Chapter 5.1, a profit margin will be calculated to assess the performance of individual charging stations or locations and enable meaningful comparisons. To calculate the profit margin, data for revenue and expenses related to the defined operation unit are necessary (see to Equation 6.1).

$$\text{Profit Margin} = \frac{\text{Net Income}}{\text{Revenue}} = \frac{\text{Revenue} - \text{Expenses}}{\text{Revenue}} \quad (6.1)$$

In this case, the analysis will follow a bottom-up approach and be done on the level of charging points, which represents the smallest logical unit within the charging infrastructure. These individual charging point can be aggregated to form charging locations (consisting of multiple charging points) or encompass the entire CPO business (comprising multiple charging locations).

Standard or benchmark values are utilized for certain factors such as investment costs or other expenses, as discussed in Chapter 6.2.2. These values are calculated by averaging data across multiple charging points rather than being specific to individual charging points.

While this approach may lose some significance when conducting detailed analyses on a specific charging point, it ensures that all analyses are based on a common and valid foundation, even in the absence of specific information.

This approach is necessary because there are instances where a direct or precise mapping of costs retrospectively may not be feasible or would require disproportionate effort.

Differentiation in benchmark values, such as investment costs, is made between HPC and AC charging infrastructure. This differentiation is crucial due to the significant differences highlighted in previous chapters between these two groups. It provides an accurate means of identifying potential areas for improvement.

6.2.1 Revenue

This subchapter provides an overview of the primary income sources for the charging infrastructure. The sale of electricity is the first and most significant source of income. As a CPO, Audi provides the charging infrastructure, including the electricity, and receives a charging fee in return. Various options exist to structure the charging fee or tariff:

- Some CPOs implement a combination of a *singular connection fee* (e.g., 99 cents per started charging process) along with a *kWh-based tariff* (e.g., 40 cents/kWh).
- In certain locations where high demand or utilization rates are anticipated, *blocking fees* can be added to the charging price after a specific duration. This practice is

often applied to high-power chargers or charging stations in urban areas with substantial charging traffic. After the charging process concludes, fees (e.g., 10 cents per minute) encourage EV drivers to disconnect and vacate the charging point promptly, making it available for other customers.

CPOs have the flexibility to choose a combination of all three accounting methods – kWh-based, time-based, and singular fee – along with different pricing levels, making the tariff system potentially complex. However, as described in Chapter 3.3, most customers avoid this complexity by utilizing bundled offers from MSPs.

As a CPO, AUDI AG has opted for a straightforward and streamlined tariff structure, exclusively using kWh-based tariffs while distinguishing between AC and HPC or DC charging. The determined prices result from internal business case considerations and competition analysis. As of February 2023, a fee of approximately 30 cents/kWh is imposed for AC charging events, and around 40 cents/kWh for HPC. It's important to note that these prices represent the net yields demanded by the CPO from the MSPs or Roaming platform. They should not be confused with the prices paid by customers, as those include the margin of payment providers, roaming hubs, MSPs, and taxes.

To calculate the total revenues from electricity sales, the net yield per kWh is multiplied by the amount of transferred or billed kWh. To facilitate later expense comparisons, the transferred kilowatt-hours were evaluated for the entire year of 2022 and balanced on a monthly basis. Figure 18 provides an overview of the projected monthly revenues from the analyzed public charging points.

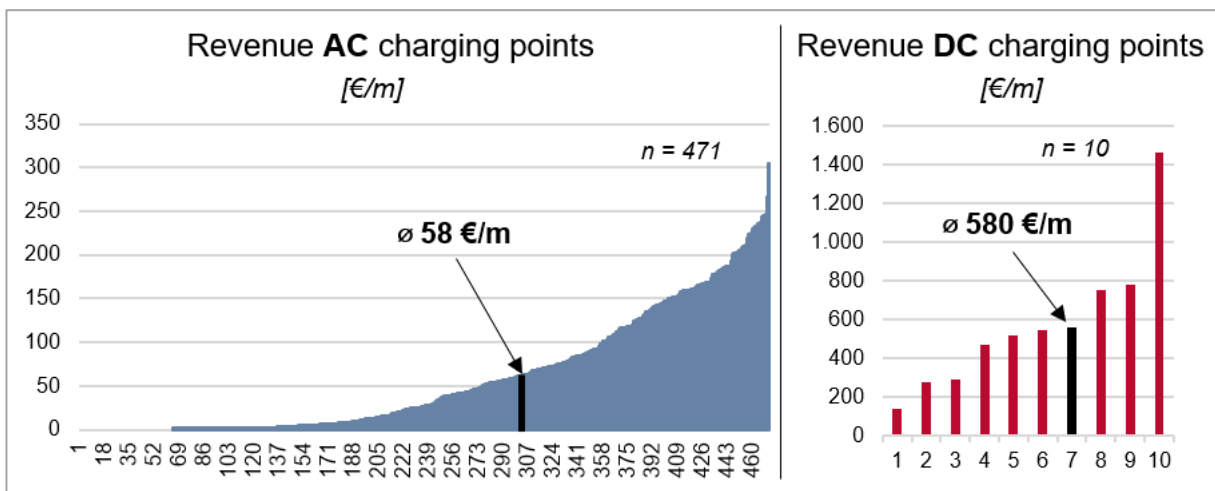


Figure 18 - Overview of charging points regarding their revenues from electricity sale (own representation)

As expected, the HPC points (n = 10) generate significantly higher revenues compared to AC charging points. The revenue ranges from approximately 136 to 1,460 €/month for HPC charging points. On the other hand, for charging points with 22 kW charging power or less (n = 471), the revenues range from 0 to 304 €/month.

A detailed analysis of the AC chargers reveals that the top values can be considered as optimal operation scenarios. The maximum revenue corresponds to around 950 kWh of energy transferred at an AC charger over a one-month period.

Considering the classic charge at work use case with one charging event of 30 kWh per day on five days a week, a theoretical energy transfer of 600-700 kWh/month (192-224 €/month) could have been expected. It can be observed that only a few values exceed this range. These “over the top values” can be explained by the three-shift operation of the Audi plant, where some charging points are used for more than one charging event per day.

On the other hand, many charging points exhibit lower revenue outcomes, indicating that they are either underutilized or sparsely utilized. This can be attributed to Audi AG's strategy of enabling and supporting electric mobility for its employees.

In some cases, the infrastructure capacity exceeds the current demand, resulting in low frequented charging points. However, as the share of BEV among employees or the general population increases, higher utilization and, consequently, higher revenues are expected.

Looking at the bar chart in Figure 18, it is anticipated that over time, the revenues of an average AC charging point will approach the optimal level. Currently, the average revenue across all installed external AC charging points is approximately 58 € (182 kWh) per month (see Table 6-1).

Table 6-1 - Average monthly transferred energy and revenues for AC charging point

| | Average monthly transferred energy | Average monthly revenues |
|--------------------------|------------------------------------|--------------------------|
| AC charging point | 182 kWh | 58 € |

The detailed analysis of the ten HPC stations reveals that the maximum revenues of 1,460 €/month (3,650 kWh/month) can be compared to a theoretical scenario with three to four charging events of 35 kWh each per day, including weekends. The bar chart in Figure 18 also highlights that some charging points significantly fall below the top revenue value.

This disparity can be attributed to factors such as different power levels (150 kW vs. 300 kW) or specific location characteristics. Unlike the AC infrastructure, the HPC units are predominantly used by various charging customers rather than employees.

Evaluating the exact influence of location or potential revenue increases is challenging. However, the chart demonstrates the gap between the best performing charging point and the lower performing ones, suggesting room for improvement. Currently, the average revenue across all installed external HPC charging points is approximately 580 € (1,450 kWh) per month (see Table 6-2).

Table 6-2 - Average monthly transferred energy and revenues for DC charging point

| | Average monthly transferred energy | Average monthly revenues |
|------------------|------------------------------------|--------------------------|
| HPC point | 1,450 kWh | 580 € |

In addition to the sale of electricity, there are other potential sources of revenue for charging infrastructure that should be considered, such as funding or incentives. Various funding schemes exist for charging infrastructure, one example being the German “Treibhausgas-minderungs-Quote” (THG-Quote), also known as the greenhouse gas reduction quota.

The THG-Quote is a mechanism introduced in Germany to reduce greenhouse gas emissions. The regulations are defined in the Federal Immission Control Act (BImSchG), which mandates fuel distributors to progressively reduce the emissions associated with the fuels they provide by a predetermined percentage. Currently, the required reduction compared to a defined base value is 6 %, and it will increase to 25 % by 2030 (cf. Bundes-Immissionsschutzgesetz. Umwelt Bundesamt).

To achieve these goals, fuel distributors have various options, including the use of bio-fuels, green hydrogen, and other methods specified in the Federal Immission Control Ordinance (BImSchV). The 38th BImSchV specifically addresses the possibility of crediting electricity used in electric vehicles, stating that the energy transferred at public charging stations is a valid option (cf. Umwelt Bundesamt, 2023)

Under this mechanism, the CPO can obtain greenhouse gas reduction certificates for every kilowatt-hour transferred at their charging station for use in electric vehicles. These certificates can then be sold on the market for THG-quota to fossil fuel providers. Revenues between 15 and 20 cents/kWh were observed in 2022.

Figure 19 illustrates the potential revenues that could have been generated from the THG-Quote for an average HPC and AC charger.

It is important to note that while these earnings can contribute to the operation, the market mechanism causes prices for reduction certificates to vary due to changing supply and demand. Therefore, they should be treated separately from earnings derived directly from the sale of electricity.

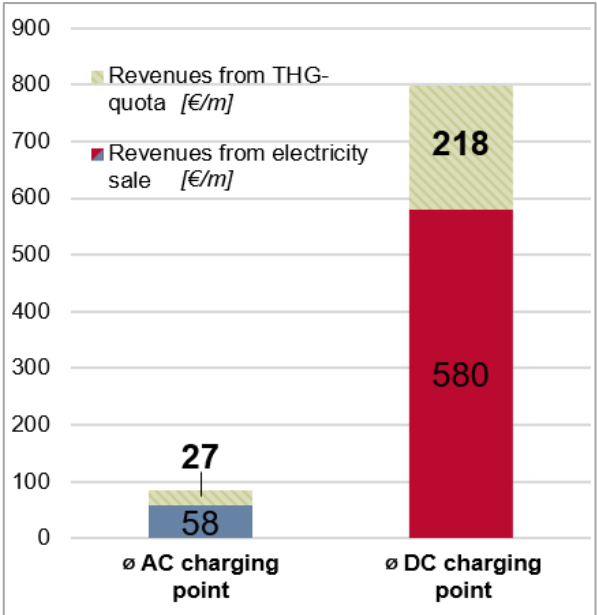


Figure 19 - Revenues from THG-quota additional to electricity sale revenue – for the average AC and DC charger (own representation)

Another conventional form of funding is financial support provided during the establishment of the charging station, which can come from federal or municipal authorities, for example. This support reduces the initial investment costs borne by the CPO. In line with this rationale, such funding would not appear as additional revenues, like the THG-Quote, but rather as a reduction in investment expenses, as discussed in Chapter 6.2.2.

6.2.2 Expenses

On the other hand, the CPO incurs various expenses. This section provides an overview of the main costs associated with the evaluated charging infrastructure.

Charging hardware

The primary cost is related to the charging equipment itself, including the hardware and initial installation. For AC charging infrastructure, an analysis of recent projects by AUDI AG indicates an average cost of approximately 5,500 € per charging point.

This finding aligns with a study conducted by the “Ludwig-Bölkow Stiftung” in collaboration with the General German Automobile Club (ADAC), which reported a maximum cost of 4,000 € for the hardware and 1,000 € for the power supply of a public charging point (cf. Bünger et al., 2019, p. 24).

To compare these costs with monthly revenues and calculate the profit margin later on, a depreciation value needs to be determined. Assuming a useful lifetime of ten years for AC infrastructure and using a static depreciation method for simplicity, the monthly costs amount to approximately 46 € per charging point (see Equation 6.2).

$$\text{Monthly Depreciation AC Hardware} = \frac{\text{Initial Costs}}{\text{Useful Lifetime}} = \frac{5,500 \text{ €}}{10 \text{ a} \times 12 \text{ m/a}} \approx 46 \text{ €/m} \quad (6.2)$$

For HPC infrastructure, the initial costs for hardware and installation are significantly higher. Recent projects carried out by AUDI AG, involving charging points with a power capacity of 150 kW or higher, indicate average costs of around 100,000 € per HPC point. Additionally, it has been observed that HPC points should be assessed with an expected useful lifetime of only five years, based on the experience gained from the first generation of HPC stations installed at the Audi headquarters. It is hoped that subsequent generations installed in the past two years or in the future will have a longer useful lifetime. Consequently, the expected monthly depreciation, as calculated in Equation 6.3, would need to be adjusted accordingly.

$$\text{Monthly Depreciation HPC Hardware} = \frac{\text{Initial Costs}}{\text{Useful Lifetime}} = \frac{100,000 \text{ €}}{5 \text{ a} \times 12 \text{ m/a}} \approx 1,667 \text{ €/m} \quad (6.3)$$

Infrastructure

In addition to the hardware, further infrastructure costs have been analyzed for the public Audi charging points. The analysis reveals that the average infrastructure costs for HPC and AC projects are similar in absolute value but differ in relation to the number of constructed charging points.

For instance, both types of projects may require a new transformer, but for HPC stations, the transformer can only serve ten charging points compared to 240 AC charging points.

In a worst-case scenario, expenses for construction or excavation work, as well as new high-voltage grid connections, must be considered. For an AC charging point, the initial investment cost for infrastructure can reach up to 1,400 €.

Since most infrastructure components have an expected useful lifetime of around 19 years, this amounts to a monthly depreciation of approximately 6 €.

For HPC points, the total cost of an additional high-voltage grid connection and the installation of a transformer is approximately 34,250 €, resulting in a monthly depreciation of 150 €.

Running costs

In addition to the aforementioned initial costs, there are several ongoing expenses that should be considered as part of the operating costs of a charging operation.

One of these expenses is related to the CPO backend. In most cases, the CPO utilizes the services of a backend service provider and pays a corresponding fee. AUDI AG uses a backend system where a basic charge is applied for the general service, and no additional fees specific to each charging point are required. Therefore, the cost allocation can be based solely on the total number of charging points. In this case, a separate calculation for AC and HPC categories was not performed since no fundamental difference in causation could be identified (there is no evidence that an HPC point incurs higher backend costs).

Another expense category is service and maintenance. For the Audi charging infrastructure, these tasks are performed by a service provider. The average expenses were derived from various maintenance contracts. On a per-charge point basis, the service fee for an HPC unit is higher than for AC charging points, which differs from the backend cost allocation.

All of the aforementioned operational costs, along with the initial costs, are listed in Table 6-3. Negative expenses or expense reductions resulting from initial investment funding are not listed, as no financial assistance was utilized for the establishment of the external AUDI AG charging infrastructure.

Table 6-3 - Overview of average monthly costs for AC and DC charging points

| Fixed costs | Cost [€/month] – AC charging point | Cost [€/month] – DC charging point |
|--|---------------------------------------|---------------------------------------|
| <i>Depreciation charging hardware (incl. installation)</i> | 46 | 1,667 |
| <i>Depreciation infrastructure</i> | 6 | 150 |
| <i>Operational costs (e.g., for backend, first level support, service and maintenance)</i> | 30 | 54 |
| Sum | 82 | 1,871 |
| Cost assumption of (Bünger et al., 2019, p. 25) for comparison | 98 (1,175 per year) | 1,283 (15,391 per year) |

In the last row, the cost assumption from *Bünger et al. (2019)* is presented. The small difference between the identified values for AC charging points reinforces their validity.

However, a significant difference can be observed for the assumed values of HPC infrastructure, which can be attributed to the varying estimated useful lifetime. *Bünger et al. (2019)* assumed a useful lifetime of 15 years for the high-power charging infrastructure, which appears optimistic.

Electricity costs

The costs associated with electricity purchase represent the only variable costs in the operation of the charging points. Similar to the calculation of revenues from electricity sales, these costs can be determined by multiplying the number of kWh used in the corresponding period by the purchase price. In the averaged scenario, the energy consumption aligns with the values presented in Table 6-1 and 6-2. (Note that charging or standby losses were disregarded; for more details, refer to Chapter 6.3).

The electricity price for most locations in the company vicinity for the year 2022 was approximately 15 cents/kWh. The corresponding average electricity costs are provided in Table 6-4.

Table 6-4 - Average monthly electricity costs for AC and DC charging points

| Variable costs | Cost [€/month] – AC charging point | Cost [€/month] – DC charging point |
|-----------------------------|------------------------------------|------------------------------------|
| <i>Electricity purchase</i> | 28 | 222 |

Limitation of transferability

The expenses and categories discussed thus far are comprehensive and encompass the primary costs associated with the construction and operation of public charging points. However, there are additional costs that could be considered for a public charging location.

Firstly, there are electricity costs associated with standby power and losses during the charging process. Currently, there is no way to track these costs at the individual charge point level. Due to their minimal impact on the overall business case assessment, they were neglected. However, in Chapter 6.3, these costs are evaluated in more detail in the context of energy efficiency.

Another expense to consider is the rental cost for the parking lot. In the case of AUDI AG, the parking area was already owned, so no additional expenses needed to be considered. However, for other projects, especially those at highway locations, lease costs are common.

One factor that was also not assessed is personnel costs. In this case, it was assumed or argued that the operation of charging infrastructure is not the core business of AUDI AG but rather a subsidiary branch that enables other services or business operations. Therefore, one could argue that personnel costs are fixed or residual costs of the core business and should not be allocated to the external charging infrastructure business case.

6.2.3 Profit margin

Depending on the relationship between revenue and expenses, the CPO can either generate a profit or incur a deficit. In the previous chapters, the focus was primarily on average values to provide an overview of the revenue and cost structure. This consolidation is summarized in Table 6-5.

For the AC charging points, it becomes apparent that the revenues related to an average energy transfer of 182 kWh per month are insufficient to cover the incurred costs. Even after considering revenues from the THG-quota, there remains a monthly deficit of -25 € per average AC charging point.

The situation is even more challenging for the average HPC point, where the significant fixed costs cannot even be offset by revenues from the THG-quota. This results in a total monthly loss of -1,259 € per connector.

Table 6-5 - Overview of average monthly costs and revenues for AC and DC charging points

| | AC charging point [€/month] | DC charging point [€/month] |
|---|--------------------------------|--------------------------------|
| <i>Fixed costs</i> | -82 | -1,871 |
| <i>Electricity costs</i> | -28 | -222 |
| Sum of costs | -110 | -2,093 |
| <i>Revenues from electricity sale</i> | 58 | 580 |
| Sum (excl. THG-quota) | -52 | -1,513 |
| <i>Possible revenues from THG-quota (15 ct/kWh)</i> | 27 | 218 |
| Sum (incl. THG-quota) | -25 | -1,295 |

However, since the primary objective of the “economic efficiency” KPI is to evaluate the performance of individual charging points, additional calculations were conducted. These calculations assessed the electricity costs and revenues for each charging point independently, while considering only the fixed costs with average values from Table 6-5.

Figure 20 provides an overview of the economic efficiency for all external charging points, distinguishing between AC and DC charging points, without considering potential revenues from the THG-quota. Instead of presenting the profit margin, the figure displays the profit or loss as an absolute value. This approach was chosen to avoid the distortion of negative profit margins due to the low utilization and small revenues of certain charging points.

The initial observation reveals that a majority of charging stations exhibit negative economic efficiency. Only a few charging points on the right side of the x-axis are profitable, and they are exclusively AC charging points with high utilization and energy transfer.

HPC points, which are analyzed separately, display the largest deficits, indicating that their significant fixed costs cannot be offset even with high utilization.

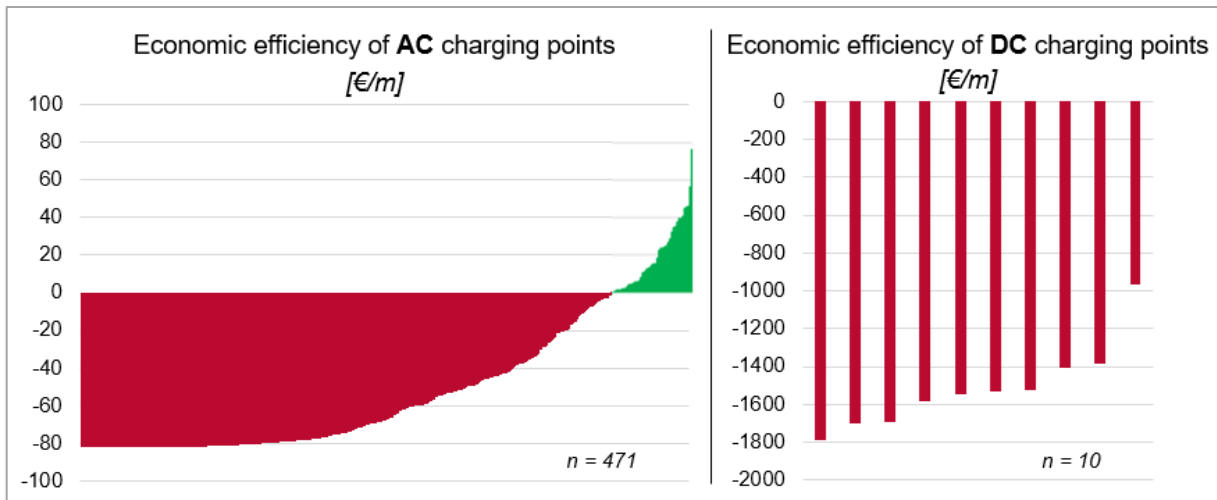


Figure 20 - Economic efficiency of every external charging point without revenues from THG-quota (own representation)

With a theoretical consideration of revenues from the THG-quota, assuming an additional 15 ct/kWh, the situation improves slightly, resulting in more AC charging points falling into the profitable sector. This can be observed in Figure 21.

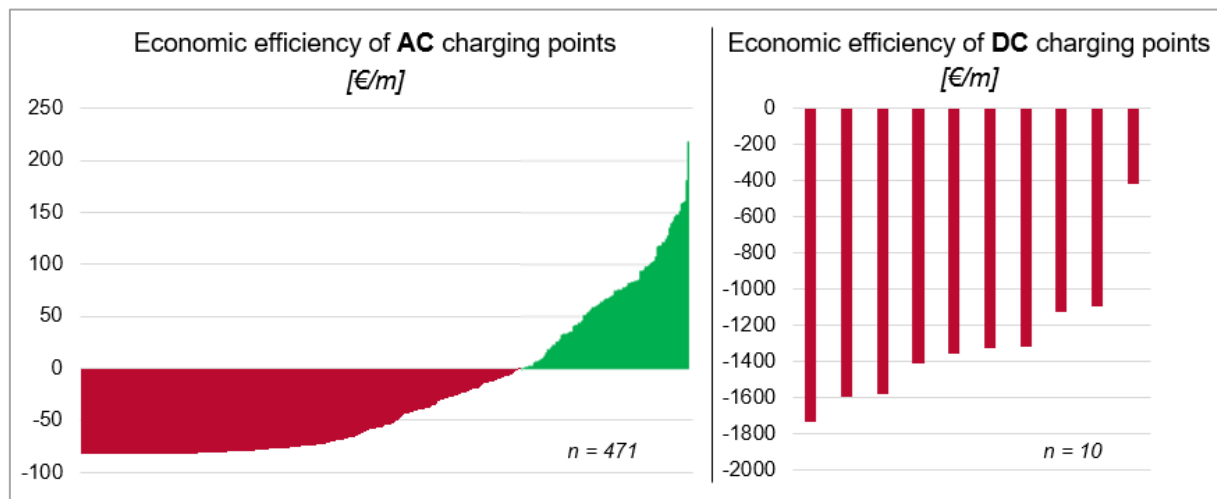


Figure 21 - Economic efficiency of every external charging point with revenues from THG-quota (own representation)

Different proposals to improve the economic efficiency can be seen in Chapter 7.1.

Limitation of this analysis

The economic efficiency calculation in this analysis adapts a static approach, for example with the depreciation of charging hardware. This simplification was chosen to facilitate the analysis and provide a valid basis for comparison, enabling the identification of trends and potential areas for improvement in the charging infrastructure.

However, it also ignores the moment of payment and therefore dynamic effects that influence the economic efficiency like interest or inflation rate. To achieve a more comprehensive perspective, it would be necessary to take these dynamic factors into consideration as well.

6.3 Analysis regarding the energetic efficiency

In the previous chapter, the electricity cost at the charging point level was derived from the energy billed to the customer, which only accounted for the transferred energy during charging. Any additional energy consumption due to charging efficiency or standby power was disregarded for the business case. However, since the CPO still incurs uncovered electricity costs, this chapter focuses on those losses that cannot be directly attributed to a specific charging event.

Ideally, in an optimized state, the energy consumption of a charging point (input) should closely match the energy transferred from the charging point to a car (output) (as shown in Figure 22). A smaller gap between input and output signifies a more efficient charging point. Conversely, a larger difference between input and output in a system's energy balance indicates significant standby or efficiency losses (or suggests other underlying issues).

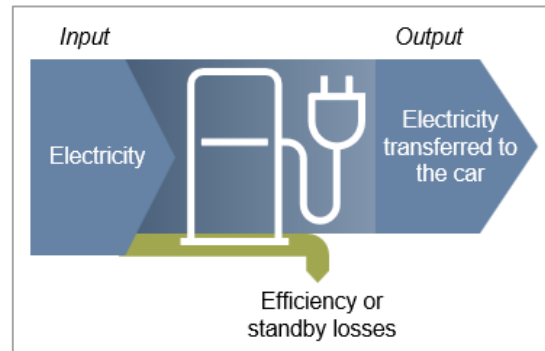


Figure 22 - Energy balance of a charging station (own representation)

The application of the energy efficiency KPI faced two major challenges. The first challenge was the availability of electricity data for each charging point, and the second challenge was the level of data aggregation that was available. During the research, it became evident that not all of the evaluated charging points were connected to electricity meters that could be accessed through an energy management system. In addition, even when meters were installed, they were not always connected to an accessible energy management platform.

Furthermore, for the charging points that were connected to accessible meters, the available data was aggregated at a group level rather than for individual charging points (as illustrated in Figure 23). This lack of one-to-one mapping prevented a clear identification of which charging point was responsible for specific electricity consumption, including losses.

In some cases, a single installed electricity meter could be monitoring up to 30 or more charging points. Without further data fragmentation, it was not possible to definitively determine the electricity consumption attributed to each charging point, including losses.

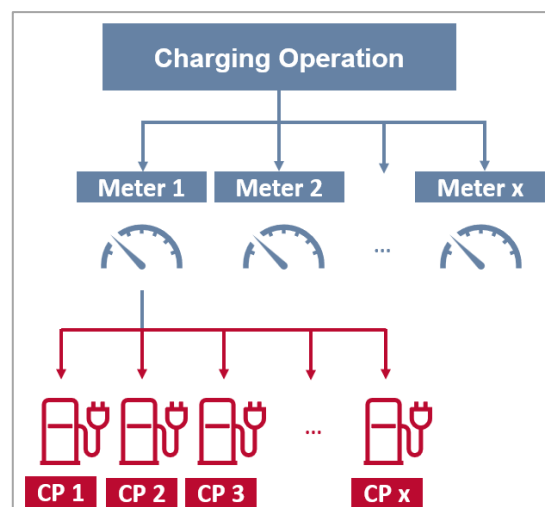


Figure 23 - Cascade of electricity meters and charging points (own representation)

The described situation had two consequences for the application of the energy efficiency KPI:

1. The KPI could not be applied to all of the previously assessed charging points due to the lack of data in some cases. As a result, the application of the KPI will be demonstrated using different examples from the subset of charging points for which data was available, showcasing the knowledge generated from its application.
2. The KPI was applied at the level of electricity meter aggregation, which encompassed charging groups consisting of multiple charging points, rather than individual charging points.

The energy demand data for these groups was obtained from an energy management system. Consequently, the total transferred energy from all the charging points within a particular group was calculated using data from the CPO backend. The calculation of the “charge group efficiency” is shown in Equation 6.4 below.

$$\text{Charging group efficiency} = \frac{\text{benefit}}{\text{cost}} = \frac{\sum E_{\text{out}}}{E_{\text{in}}} \tag{6.4}$$

Σ: Sum of all charging points connected to the same electricity meter
E_{out}: Electrical energy transferred from charging point to car
E_{in}: Total electrical energy demand of the charging infrastructure

Figure 24 illustrates various examples of charging groups and their corresponding charging group efficiencies, calculated for the month of April 2023.

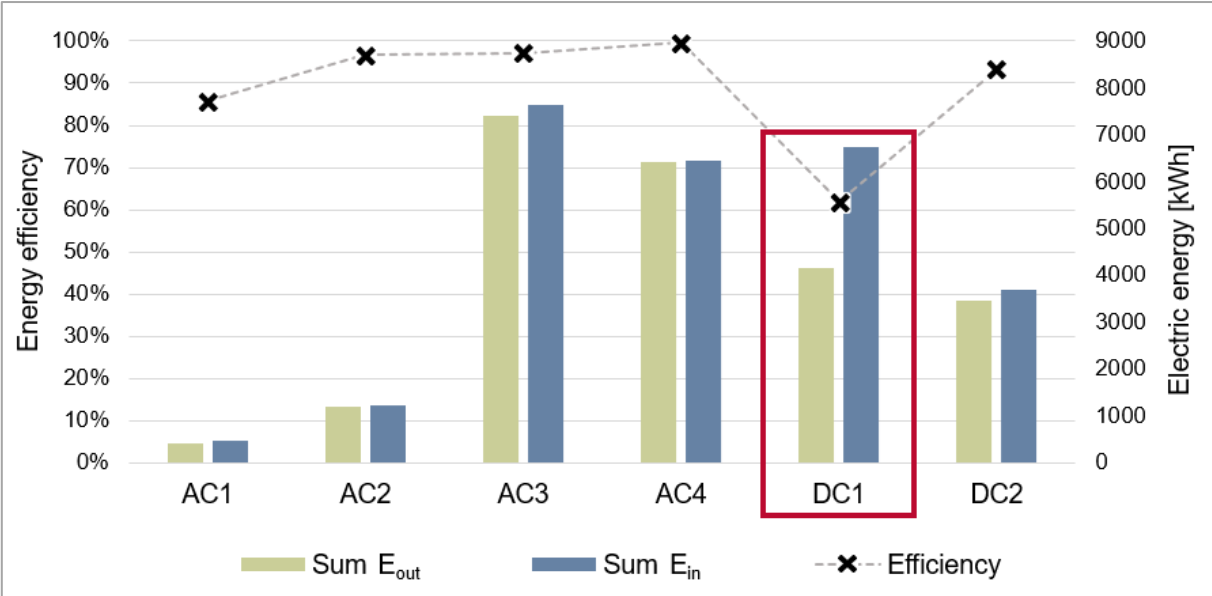


Figure 24 - Charging group efficiency for selected locations (own representation)

The first four sections of the figure represent AC locations, which exhibit good energy efficiencies ranging from 86 % to 99 %. A detailed analysis of the first value for charging group “AC1” revealed that a single charging event that occurred at the month boundary was not included in the April data due to the backend algorithm. Consequently, the recorded electricity meter value for that event, which extended until the month boundary, was slightly higher. Given the low overall transferred energy at this location, this discrepancy had a significant impact on the efficiency calculation, introducing uncertainty. However, the other AC charging locations with higher energy transfer volumes were less affected by such uncertainties and demonstrated efficiencies between 97 % and 99 %. These high values indicate both efficient charging processes and low standby consumption. Specific values for standby consumption can be found in Table 6-6.

Table 6-6 - Electrical standby consumption of selected AC charging locations

| Name | Location | Charging equipment | ∅ Standby consumption |
|------------|--------------|--------------------|-----------------------|
| AC1 | <i>A51</i> | 14 x 22 kW | 0 kW |
| AC2 | <i>Forum</i> | 8 x 22 kW | 0 kW |
| AC3 | <i>N69</i> | 15 x 22 kW | 0 kW |
| AC4 | <i>T39</i> | 14 x 22 kW | 0 kW |

Groups five and six in Figure 24 represent locations equipped with DC charging hardware. Cluster “DC2” was assessed with an efficiency of 93 %, similar to the AC infrastructure, and thus requires no further investigation.

In contrast, location “DC1” exhibits an efficiency of only 62 %. A detailed analysis uncovered that the main factor contributing to this poor performance is a significant standby consumption of approximately 3 kW. Further examination revealed that out of the total registered energy consumption of 6,700 kWh in April, around 2,100 kWh were associated with standby consumption.

To ensure that this was not a data error specific to this location, additional locations with accessible data were examined. These internal locations, which are beyond the scope of the other analyses conducted in Chapter 6, are listed in Table 6-7 along with their average standby consumption values.

Table 6-7 - Electrical standby consumption of selected DC charging locations

| Name | Location | Charging equipment | ∅ Standby consumption (Range of standby cons.) |
|-----------------|-------------------------|--------------------|---|
| DC1 | <i>Forum (external)</i> | 4 x 350 kW | 3 kW (2.8 – 3.3 kW) |
| DC2 | <i>S49 (external)</i> | 2 x 150 kW | 0 kW |
| Compare1 | <i>S49 (internal)</i> | 2 x 150 kW | 0 kW |
| Compare2 | <i>S20 (internal)</i> | 4 x 350 kW | 3 kW (2.4 – 3.4 kW) |
| Compare3 | <i>S48 (internal)</i> | 4 x 350 kW | 3 kW (2.5 – 4.4 kW) |

It can be observed that two other locations also exhibit higher standby consumptions. The subsequent analysis revealed a connection between poor performance and a specific type of charging hardware in combination with a specific electrical topology. In all cases, this particular charging hardware relies on a separate isolating transformer with an idle power of 1 kW. The other HPC locations with better efficiency utilize different hardware and do not require a separate isolating transformer.

The application of the energy efficiency KPI highlighted the significant influence of standby power. As a result, it is suggested to directly utilize the average standby consumption as a KPI for future analyses. This approach would simplify the calculation of energy efficiency and mitigate uncertainties associated with the required data.

Chapter 7.2 will present various proposals to improve energy efficiency. One of these proposals is based on the influence of the utilization of the location. In the case of charging points with high idle power being used only once a day, all the standby losses are concentrated on that single charging event. In contrast, locations with higher utilization still experience standby losses but to a lesser extent. A detailed analysis of utilization can be found in the subsequent Chapter 6.4.

6.4 Analysis regarding the utilization

The previous section provided partial information about utilization and potential correlations. The aim of this chapter is to complement the available data and analyze the overall utilization of AUDI AG's external charging infrastructure.

To achieve this, the asset utilization, as defined in Chapter 5.3, was calculated for each charging point according to Equation 6.5.

$$\text{Asset Utilization} = \frac{\text{Charging Time}}{\text{Business Hours}} \tag{6.5}$$

Therefore, the total charging times of all events at a specific charging unit were aggregated for an entire month and then divided by the business hours.

In the case of the AC charging infrastructure, which is primarily used for charging during working hours, the business hours were initially considered to include only workdays from Monday to Friday. However, it was determined that the propensity for a specific use case does not affect the business hours. As a result, this limitation was deemed unnecessary and omitted from the calculation.

For the HPC locations situated around the company grounds, where the focus is on being available for spontaneous charging events and enabling short charging stopovers with high energy transfer rates, no time slots were excluded from the calculation.

An overview of the identified asset utilizations is shown Figure 25. The data reveals a wide range of utilization rates, ranging from 0 % where no charging events were registered for specific charging points, to a maximum utilization rate of 26.7 % for AC charging points.

The average asset utilization for AC charging points is 6.9 %. For DC charging points, the maximum utilization rate is 6.5 %, with an average asset utilization of 3.0 %.

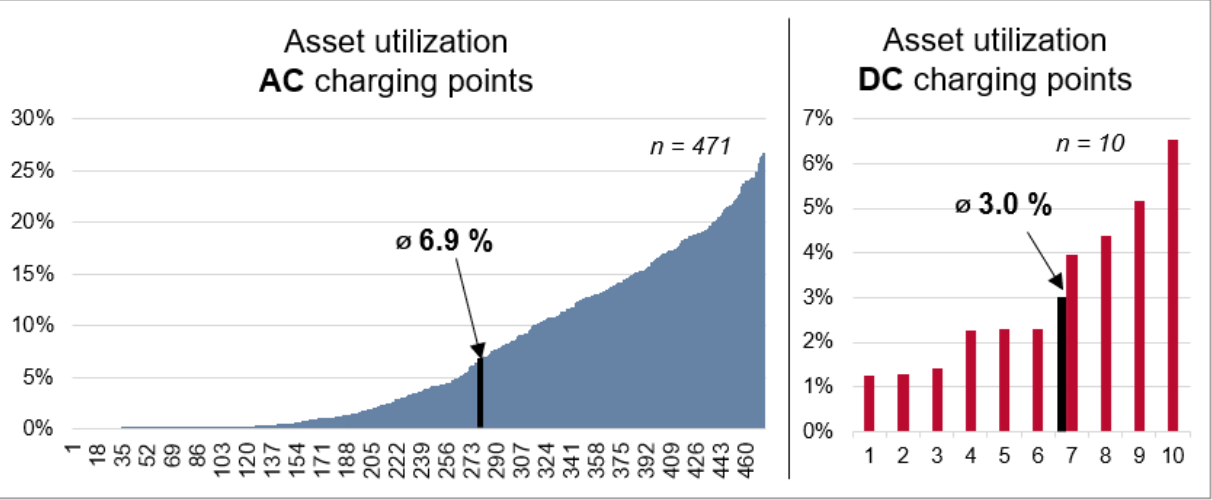


Figure 25 - Asset utilization of every external charging point (own representation)

A possible explanation for the low utilization of some AC charging points is the anticipatory construction of charging infrastructure and the focus on the charge at work use case. The construction of charging points in anticipation of the transition from combustion cars to electric cars leads to an excess of charging infrastructure during the initial phase.

Additionally, the limited user base of AC charging points, oriented at employees, limits the demand for these charging points. In contrast, public charging infrastructure located in central parking lots can attract demand from any person in need of charging. As the share of BEV among employees increases and the supply of charging infrastructure meets the base demand, it is expected that currently underutilized charging points will naturally experience increased utilization.

However, it should be noted that a higher BEV share and increased charging demand may not have the same impact on already well-performing charging points. Factors such as pricing levels and physical availability can limit the maximum utilization rate of these charging points.

The situation is fundamentally different for HPC locations. Due to their appeal to a wider range of customers, there is typically a base demand for these charging points. This is reflected in the fact that there are no HPC units with a 0 % utilization rate. For the CPO, low or suboptimal utilization rates for HPC locations can have various causes and require more complex analysis. Possible explanations range from technical faults to inadequate user-friendliness or a weak competitive position. Chapter 7.3 will delve into causal explanations, correlations with other factors or KPIs, and explore potential areas for improvement.

At this point, a comparison can be made between the best and worst performing charging points within a group to identify performance benchmarks. For AC technology, the most utilized charging location with a utilization rate of 26.7 % can serve as the benchmark for other charging points in the same category.

For HPC units, the internal benchmark is set at 6.5 %. Given their more immediate competitive position, it is also possible to compare them to other public charging infrastructure that is not necessarily owned by AUDI AG but operates under similar conditions.

HPC units should aim to achieve utilization rates comparable to the competition. However, accessing values for comparison can be challenging, and even when information is available, classification can be difficult.

Dr. Marcus Groll, the Chief Operating Officer of Ionity, which is a central CPO for fast charging at highways in Europe, stated in an interview that their plan is to achieve an overall utilization rate of approximately 20 %. He also mentioned that peak utilization rates ranging from 30 % to 40 % can be expected during the summer months. (cf. Rudschies, 2022)

The available indications from the competition should be approached with caution as they often lack specific details on the calculation method or a clear reference figure (e.g., asset or capacity utilization).

Another approach to gauge utilization is through average energy transfers, as demonstrated in scientific studies such as the survey conducted by the German National Centre for Charging Infrastructure on charging infrastructure projections for 2025/2030 (Nationale Leitstelle Ladeinfrastruktur, 2020a), as shown in Figure 7.

By dividing the expected average energy transfer for different types of charging points (e.g., work, or urban charging hubs) by their maximum possible output, an average capacity utilization can be derived (see Equation 6.7 and 6.7).

$$\text{Capacity Utilization (AC, Work)} = \frac{\text{Charged Energy}}{\text{Maximum Output}} = \frac{9.3 \text{ kWh/d}}{22 \text{ kW} \times 24 \text{ h/d}} \approx 1.8 \% \quad (6.6)$$

$$\text{Capacity Utilization (HPC, Urban)} = \frac{\text{Charged Energy}}{\text{Maximum Output}} = \frac{172.5 \text{ kWh/d}}{150 \text{ kW} \times 24 \text{ h/d}} \approx 4,8 \% \quad (6.7)$$

For AC charging infrastructure at the workplace, the quoted study deduced an average energy transfer of 9.3 kWh per connector per day (cf. Nationale Leitstelle Ladeinfrastruktur, 2020a, p. 69). Considering the weekend as well, this translates to a capacity utilization of 1.8 %.

In the case of an urban HPC station with a maximum capacity of 150 kW, the same study projected an average energy transfer of 172.5 kWh per day (cf. Nationale Leitstelle Ladeinfrastruktur, 2020a, p. 69), resulting in a capacity utilization of 4.8 %.

The performance of AUDI AG infrastructure compared to those values can be seen in Figure 26.

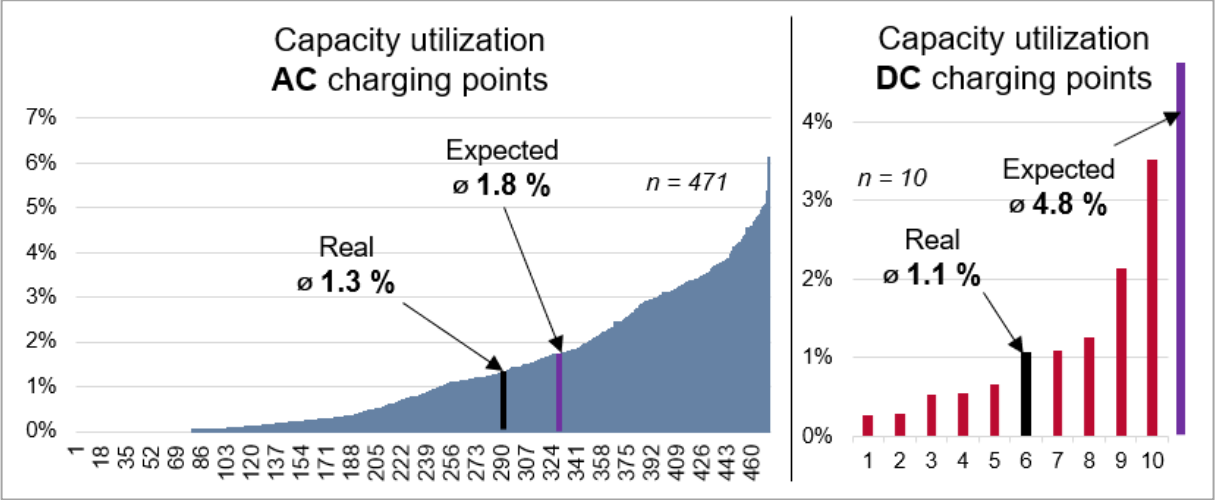


Figure 26 - Capacity utilization of every external charging point (own representation)

The capacity utilization exhibits a similar distribution pattern as the asset utilization, but with a slight shift in the coefficients.

In the case of AC charging stations, it can be observed that approximately 140 points meet or exceed the expected capacity utilization of 1.8 %. However, when considering all AC charging points as a whole, the average capacity utilization is 1.3 %, which falls 0.5 % below the expected value.

This 0.5 % difference for a 22 kW connector can be translated to approximately 2.6 kWh per day (as per Equation 6.8) that would need to be recharged additionally at the average connector to match the expected value. Over the course of one week, this would accumulate to around 18.5 kWh, which corresponds to about two-thirds of the energy amount consumed during a typical AC charging event.

Necessary Additional Energy Transfer

$$\begin{aligned}
 &= (\text{Expected Utilization} - \text{Real Utilization}) \times \text{Installed Power} \times 24 \text{ h/d} \quad (6.8) \\
 &= (1.8 \% - 1.3 \%) \times 22 \text{ kW} \times 24 \text{ h/d} = 2.64 \text{ kWh/d}
 \end{aligned}$$

The HPC chargers exhibit an average capacity utilization of 1.1 %, which is less than a quarter of the expected value of 4.8 %. It is noteworthy that even the most utilized HPC charging point in this dataset, with a utilization rate of 3.5 %, falls short of reaching the target value.

Chapter 7.3 provides various proposals to enhance the utilization of both AC and HPC infrastructure, along with their correlations to other KPIs.

6.5 Analysis regarding the usability

Next to the previously observed utilization, the usability of a charging point is another crucial key performance indicator. In order to assess the usability, the data from the entire year 2022 was analyzed to determine the number of successful and failed charging events. As outlined in Chapter 5.4, the usability was calculated for each charging point to evaluate the reliability and functionality of the infrastructure.

For charging stations that did not have any charging events during the assessed period, it is not possible to calculate a usability value (see Equation 6.9).

$$\text{Technical Usability} = \frac{CP_{\text{success}}}{CP_{\text{total}}} = \frac{CP_{\text{total}} - CP_{\text{technically flawed}}}{CP_{\text{total}}} \quad (6.9)$$

Additionally, charging points with less than five charging events in the measurement period (January 1st to December 31st, 2022) were excluded from the usability analysis due to their limited significance. Figure 27 presents the usability analysis for the remaining 373 AC charging stations.

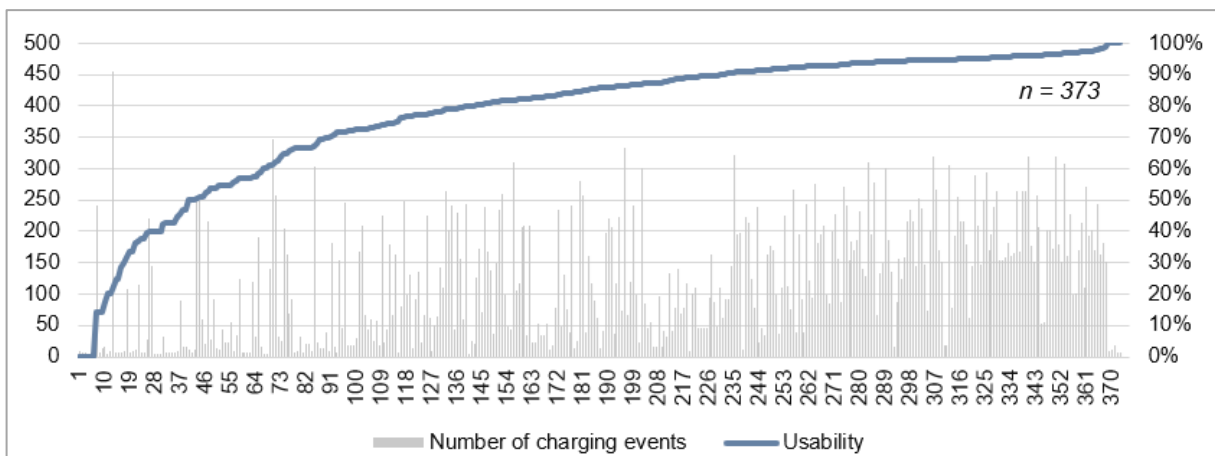


Figure 27 - Usability of AC charging points (own representation)

A preliminary assessment reveals that a significant number of charging points (285) exhibit a relatively high usability of 70 % or higher. Out of these, 234 charging points have a usability of 80 % or higher, and 144 charging points surpass the 90 % usability mark. However, there is still a notable portion of charging points (42) with a usability of 50 % or lower. In practical terms, this indicates that at least half of the charging events at these stations are unsuccessful. The average usability across all AC charging points stands at 78 %.

In addition to the usability, the number of charging events associated with each charging point is displayed, as it serves as the sample size for the calculation. In Chapter 7.4, when identifying opportunities for improvement, particular attention will be given to charging points with low usability but a high total number of charging events. These cases will be examined in conjunction with the question of what level of usability should be targeted and what level is considered acceptable.

No charging points in the HPC infrastructure had to be excluded due to a small sample size. The usability of these charging points is displayed in Figure 28.

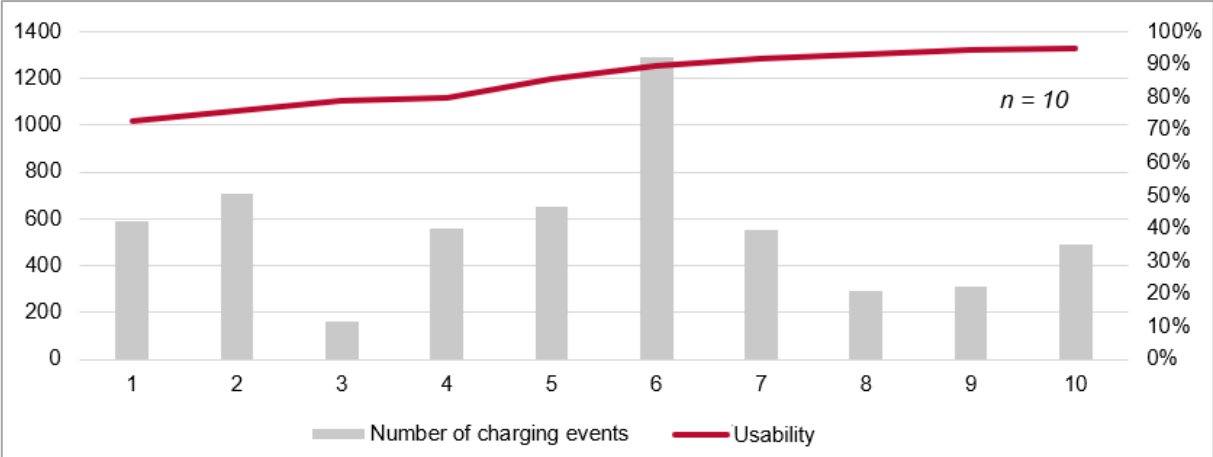


Figure 28 - Usability of DC charging points (own representation)

The average usability of all DC charging points is 85.5 %. It is evident that the usability of HPC stations is generally higher compared to AC infrastructure, ranging from 73 % to 95 %.

However, even though the performance is better overall, there are four DC charging points with a usability below 80 %. This corresponds to approximately 480 failed charging events throughout the year 2022.

These figures indicate potential for improvement, which will be analyzed and linked to various proposals for optimizing usability in Chapter 7.4.

6.6 Analysis regarding the user-friendliness

Due to capacity limitations, the designed user-friendliness list could not be applied to all 481 charging points. Instead, a selection was made, focusing on three different types of charging points located around the headquarters, for an exemplary application of the evaluation scheme (see Appendix). The objective was to identify challenges encountered during the evaluation process and provide examples that demonstrate varying degrees of fulfillment or importance across different user-friendliness categories.

Selection of (representative) charging points

1. The first charging point to be examined was an AC Wallbox (with the EVSE-ID *DE*AUC*ETRON*00349*) installed in a parking deck (T33A). This charging point represents approximately 250 other external charging points that are clearly oriented at the charge at work use case.
2. The second charging point (with the EVSE-ID *DE*AUC*ETRON*00150*) is also oriented towards the charge at work use case and equipped with the same hardware. However, it is located in an open parking space (P11) instead of a parking deck.

-
3. The third charging point (with the EVSE-ID *DE*AUC*E02E*H0001*4*) serves as an example for HPC infrastructure. Unlike the other two charging points, its use case is not limited to a charge at work scenario but encompasses public charging in general. This charging point, located in the open at the Audi Forum in Ingolstadt, is capable of delivering charging powers of up to 350 kW.

Assessment of obligatory aspects

1. Consistency in the use of the EVSE-ID

All assessed charging points used the EVSE-ID consistently. No significant differences were observed.

2. Careful placement of EVSE-ID to preclude mix-ups

The EVSE-ID was placed carefully in all cases. For AC charging infrastructure, the EVSE-ID was positioned above the charge port, ensuring easy identification. In the case of the HPC charging point, the EVSE-ID was located directly on the charging station, ensuring accurate mapping. However, it should be noted that several other numbers or IDs, such as inventory, serial, or meter numbers, were present on the charging points. Although none of these were incorrectly labeled as EVSE-ID, the presence of multiple IDs on the charging infrastructure may create uncertainty for some users.

3. Easy identification and readability of controls with no influence of varying weather conditions

Due to differences in hardware and placement (parking deck or open space), variations in control identification and readability were observed. For AC charging hardware, the controls and displayed information were minimalistic. The small control screen, positioned at eye level, was easily detectable, and within the parking deck location, good readability was consistently ensured. In open spaces, readability remained feasible, but strong sunlight from unfavorable angles affected visibility.

Similar observations were made for the HPC charging pole. Unlike AC hardware, HPC units were equipped with larger control panels to display more information. Since a significant part of the control concept relied on the touchscreen, the negative impact of sunlight had a greater influence on user-friendliness at the HPC station. Measures to improve this aspect are discussed in Chapter 7.5.

4. Standardization of URLs related to the QR codes

All assessed charging stations utilized standardized QR codes and URLs, ensuring user-friendliness in this aspect.

5. Instructions of all possible ways for authentication on the charging station

In terms of providing information for authentication, the AC and HPC infrastructure differed in their approach. As previously mentioned, the HPC unit prioritized touchscreen

interaction for displaying information and control aspects. One method of authentication (via MSP) had excellent information displayed on the control screen. However, for ad-hoc charging authentication, the information was presented on a label, which also included the necessary QR code. Having the authentication information displayed in two different ways and at different locations on the charging station was deemed suboptimal in terms of user-friendliness.

For the AC charging infrastructure, no authentication information was displayed on the control screen but rather imprinted on the charging station itself. Similar to the HPC station, the imprint only showed the validation procedure via MSP, while the information for ad-hoc authentication was displayed on a separate label.

6. High visibility of service hotline of the CPO on the charging station

On all charging stations, the service hotline was prominently displayed on a red label with good contrast. The label size and hotline information were appropriate in relation to the overall appearance of the charging station.

7. Good detectability and clear signage towards the charging station

None of the assessed charging stations had signage that could be considered sufficient. There were no street signs indicating the availability of charging infrastructure at the parking deck or lot from a distance, nor were there signposts directing users to the specific charging location within the parking deck or lot. This lack of signage is unfavorable for AC charging infrastructure, but it can be partially excused due to its orientation towards the charge-at-work use case. It can be assumed that employees who are willing to use the charging infrastructure are already familiar with the parking location, and even if the charging location is not immediately visible, they will be willing to search for it. Once employees find the charging location, they can use it for subsequent instances without signs guiding the way.

However, a different situation was observed for the HPC infrastructure. The lack of signage poses a significant problem that cannot be excused solely based on the use case orientation. As mentioned earlier, HPC charging points are often used by various customers with spontaneous charging needs. These customers are likely unfamiliar with the parking situation and may have limited willingness or opportunity to search for the charging location. Unlike employees, their interaction with the charging infrastructure may not be repeated regularly. Therefore, the inadequate detectability of the charging location has a clear negative impact on the user-friendliness of the assessed HPC point.

Assessment of optional aspects

Not all optional user-friendliness aspects will be discussed here, as the knowledge gained for some aspects is limited. The focus is primarily on aspects with significant deficits or notable differences among the assessed charging points.

One aspect with a general deficit is the transparent pricing before and after charging. None of the charging points offered a consistent solution. This is caused by the various payment options. For ad-hoc charging, where the CPO knows and sets the price, the cost per kWh is displayed for the customer within the web application that is needed to start the charging process.

However, if the payment is done via an MSP, the CPO does not know about the payment conditions of the customer. The CPO only has information about the contract conditions between the MSP and themselves as an intermediary, but not about the specific contract between the MSP and the customer. Consequently, the CPO is unable to display the effective price to the customer at the charging station.

Hence, the assessed deficit is not specific for a group of charging points but caused by the overall payment structure of the public charging sector.

The next aspect that will be considered is the implementation of a user-experience (UX) concept at the charging stations. Two different approaches were observed. In both cases, the UX elements were integrated into the charging hardware itself, rather than the entire location.

For the AC charging infrastructure, light and sound signals provided feedback or indication during the authentication process. In the case of ad-hoc charging, additional information was also provided through the web application displayed on the customer's smartphone.

For the HPC station, the UX was centralized and focused on a large touchscreen, where a wealth of information and instructions were displayed, supported by light signals at the charging port or the top of the charging station to indicate success (green light) or error (red light).

In both cases, the UX concept appeared fragmented, which worked well for RFID card authentication. However, for ad-hoc charging, there was a gap in the user experience and customer journey as EV drivers were left to navigate the instructions displayed on the web application on their smartphones. Only the end result of successful or failed authentication and communication between the car and charging infrastructure was displayed, with no information about the steps in between.

This is understandable, as CPOs are expected to accommodate various payment options, each requiring a specific UX concept or integration. In most cases, the effort required to do so was reduced by focusing on a specific customer journey.

For other aspects such as “acceptance of various payment forms”, “compatibility with mobile apps or navigation systems”, or “adequate lighting”, no significant deficits or differences were found among the assessed charging points.

As mentioned in Chapter 5.5, during the definition of the user-friendliness checklist, some aspects were disregarded in the evaluation because they were not applicable to the specific charging points. For the assessed AC charging infrastructure with its focus on the charge-at-work use case, the aspect of “integration with other services” was excluded, for example.

Chapter 7.5 presents various proposals to improve user-friendliness and addresses aspects that have an impact on this category.

6.7 Analysis regarding the predictability

As described in Chapter 5.6, two aspects of the charging infrastructure are of particular interest to the grid operator: peak power level and peak shaving potential (refer to Table 6-8).

Table 6-8 - Values of interest for predictability of charging infrastructure

| | |
|--|--------|
| Peak power level | kW |
| Peak shaving potential (or % of charging point with smart charging capability) | kW (%) |

Similar to the challenges encountered during the application of the energy efficiency KPI, the availability of data or documentation for the assessed charging infrastructure did not allow for a comprehensive application of the predictability KPI. Nonetheless, this chapter will present the available information and provide relevant commentary. Furthermore, an outlook on planned and potential demand-side management measures will be provided.

The power level of the charging infrastructure is always dependent on the utilization of the assets. Higher utilization results in a higher power demand for the charging infrastructure. The peak power demand is associated with the maximum utilization of the charging infrastructure. In the case of the assessed charging locations, as well as newly constructed ones, a scenario in which all charging points are being used represents the situation with the highest charging demand and, therefore, the peak power level.

Disregarding other limitations, the peak power level could be calculated by summing up the theoretical charging power of all assessed charging points. For the 481 charging points considered in Ingolstadt, this would correspond to a peak power of 12,801 kW (12.8 MW).

However, as mentioned earlier, this value only represents the capacity of the charging hardware in a scenario of maximum utilization. It does not consider other factors, such as the electrical design of the installations preceding the charging point, which physically limit the maximum charging power. In most locations, especially AC charging locations, the electrical installation is not designed for 100 % utilization due to economic considerations. Typically, the power lines can only support approximately 30 % of the theoretical maximum power output that the charging hardware is capable of in theory.

For an exemplary location with ten 22 kW chargers, the charging hardware offers a theoretical maximum charging capability of 220 kW. However, the electrical installation is only designed to handle approximately 30 % of that capacity, resulting in a real maximum power of around 70 kW.

In a scenario where all charging points are simultaneously used at full load, a current reduction to 10 amperes (A) instead of 32 A would limit the charging power. Consequently, the connected cars would be charged at approximately 7 kW instead of 22 kW. In cases where the sum of charging demands does not exceed the installation limits, no current reduction is necessary, and the individual charging points can deliver up to 22 kW.

This undersizing of electrical lines or components is typically observed in locations with multiple charging connectors, where either a 100 % demand scenario is not expected, or a reduced charging power can be accepted compared to the economic cost of a larger charging electrical installation.

Conversely, in the case of a single wall box at a private residence, the 100 % demand scenario is always reached when a car is connected. Therefore, any limitation in the charging power would affect all charging processes at that location.

For HPC infrastructure, the situation is different. In some cases, both the hardware and the electrical installation are designed in a way that the maximum charging power of the charging hardware can be achieved in all utilization scenarios. This holds true for the assessed DC charging points in Ingolstadt. In other cases, the electrical installation may cover approximately 50 % of the maximum charging power of the connectors.

For a location with two 300 kW connectors, this could result in the following scenario. If one car was connected to one of the chargers a maximum charging power of 300 kW could be reached.

If then a second car would connect to the second charging point being supplied by the same electric installation, the charging power for the first car would be reduced to 150 kW and the other 150 kW would be used by the additional car.

To approximate the peak power level of the assessed charging infrastructure, the theoretical power of the AC connectors was considered with a limit of 30 %, while all HPC locations were considered with 100 %. This sums up to a peak power of 5,555 kW (5.6 MW), compared to the theoretical capability of the hardware of 12.8 MW.

Unfortunately, due to the lack of additional documentation, a more detailed analysis regarding the peak power was not possible. This would have involved analyzing groups of charging infrastructure connected to the same grid connection point.

For the second aspect of this KPI, the peak shaving potential or demand side management, different levels can be identified.

The first level involves the limits set by the electrical installation, which were previously mentioned. This basic form of demand side management is a simple and physical measure that helps increase the predictability of the power demand of the charging infrastructure, as depicted in Figure 29.

In addition to these static and local measures, demand side management can be further enhanced through the CPO backend, enabling more advanced and intelligent controls of the charging system. By adopting this approach, dynamic demand side management can be implemented globally across the charging system.

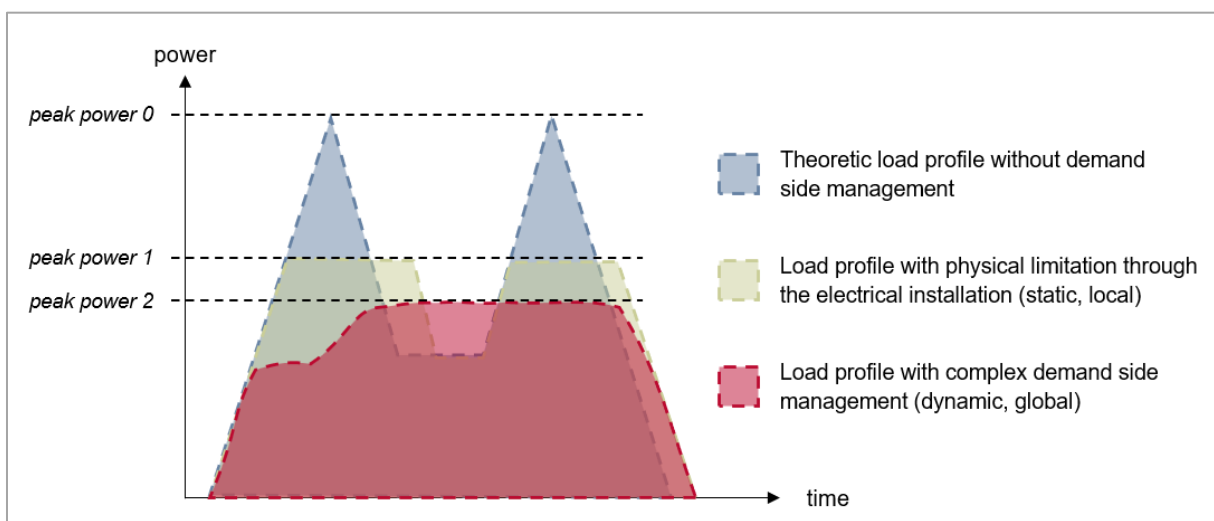


Figure 29 - Schematic load profile for different forms of demand side management (own representation)

Currently, the assessed charging points only have local demand side management capabilities. A global form of demand side management, supported by the backend, is not yet implemented but is planned and roughly designed for the future. Once implemented, it will offer the following options:

- Creating clusters for several charge points and assigning individual kW limits to each cluster.
- Setting kW limits for different times of the day or week.

These options will provide flexibility in managing the charging power of specific groups of charging points. For example, it will be possible to limit the charging power during the initial hours of the working day and shift a portion of the charging processes towards the midday period, as illustrated in Figure 29.

7 Identification of potential for improvement

Formulating goals for improvement can easily be accomplished using KPIs. However, it is important that these goals are SMART - specific, measurable, achievable, relevant, and time-bound. This ensures that they provide valuable insights into performance and progress.

Chapter 6 analyzed the charging infrastructure based on the defined KPIs. This chapter now aims to identify potential areas for improvement in each category and formulate SMART goals accordingly. Additionally, specific proposals to reach the set goals for AUDI AG charging infrastructure will be made and their qualitative mode of action will be outlined.

The proposed measures will vary in their applicability, with some focused on operational enhancements, while others concentrate on the planning process and future installations of charging infrastructure.

It is important to note that those measures will only display a selection of possibilities specifically for the assessed charging infrastructure. That means that any transferability to other (public) charging infrastructure is possible but not guaranteed and that the presented selection of measures is not exhaustive. There may be other options available to improve the KPIs that are not mentioned here.

Additionally, it should be recognized that certain proposed measures will have an impact on multiple KPIs. The initial association of these measures with specific KPIs, as well as their subsequent influence on others, will be demonstrated. Correlations between different KPIs will aid in anticipating the effects of various proposals.

7.1 Potential for improvement regarding the economic efficiency

This chapter will explain why the KPI economic efficiency should be improved, define specific goals, and outline concrete measures that can be taken to achieve these goals.

Why should the KPI be optimized and what is its current status?

Efficient economic performance is a key concern for any party with an economic interest, as it is essential for securing the competitiveness and sustainability of their operation or system. In the case of charging infrastructure, the CPO is interested in optimizing the economic efficiency of the charging points. Based on the analysis in Chapter 6.2, only few of the AC charging points can be operated with a positive economic efficiency and none of the DC charging stations. This implies a necessity for striving for higher revenues or reducing losses per charging point per month.

What goals can be formulated for addressing the situation?

Accordingly, the following SMART goals have been developed:

1. ***“Optimize the operation of all assessed AC charging points within the next two years, ensuring they operate at a minimum of cost-covering level.”***

This goal is of utmost importance as it is unsustainable for any business to consistently operate at a loss. At the same time, while striving for improved economic efficiency the current situation needs to be considered realistically. Since the primary purpose of the AC charging infrastructure is to enhance the attractiveness of the employer it would be inadvisable to aim for maximized profits.

For HPC infrastructure the following business goal is derived from the analysis of the present situation:

2. ***“Reduce the losses associated with the operation of the assessed DC charging infrastructure by at least 50 % on average within the next two years.”***

To achieve both of these goals, various measures can be employed. By following the logic of the KPI calculations, where revenues and costs were assessed independently before determining the profit or loss, these measures can be linked to either the income or expense side. The following subchapters will outline exemplary steps and their potential impact on the cost or revenue side.

7.1.1 Cost

To optimize the economic efficiency of charging infrastructure, which is the essence of the before defined goals, it is possible to minimize the costs. Lower costs in combination with steady revenues improve the profitability of the charging infrastructure. The following two measures are specific for the assessed public charging infrastructure in Ingolstadt. Their transferability will be commented.

Lower costs related to depreciation through the use of less expensive hardware

Particularly for DC charging points, depreciation costs constitute a significant portion of the overall expenses. Measures to influence the height of depreciation for different projects can most naturally only be applied during the planning phase. In that phase it is possible to consider less expensive charging hardware to fulfill the same charging demand.

One measure could therefore be to use AC charging equipment instead of DC charging equipment. As seen in Chapter 6.2.2 HPC infrastructure has disproportionately high costs. If the charging demand can only be fulfilled with HPC technology, these costs have to be accepted. But it is advisable to question any charging equipment demand and evaluate if the underlying use case could be fulfilled with AC charging infrastructure.

If this is not possible a special type of HPC hardware, which includes buffer storages, offers an alternative that can lead to cost reduction. By integrating an electric energy storage, the charging pole is able to offer high peak powers without necessarily relying on an equally powerful electricity supply. If the additional costs of the integrated buffer storage are lower than the necessary infrastructure costs for transformers or power lines a positive effect on the overall investment cost can be achieved.

Various companies offer that kind of HPC station with different storage sizes, input/output power levels, and features. For instance, Volkswagen Group Components manufactures a product called the *Flexpole*, which provides a maximum DC output of 250 kW.

It includes an integrated battery with a net capacity of approximately 190 kWh (160 kWh usable capacity). The *Flexpole* can be connected to a 400 V grid with a 63A line (~43 kW) (cf. Volkswagen Group Charging GmbH, 2023).

However, it should be noted that the application of this measure can only be assessed when the charging equipment demand is clearly understood. Different charging hardware options may have limitations in fulfilling various use case scenarios.

Retrospective analyses of existing charging locations can be conducted to assess the applicability of *Flexpoles*.

An analysis of the assessed HPC locations revealed that six out of ten charging points could have been installed as Flexpoles, while still meeting the charging requirements in the same manner as the actually used charging hardware.

However, at four locations, the charging processes would have been significantly affected. These stations have high charging demand, surpassing the buffer storage's capacity to bridge the gap between the installed power supply and the required charging power.

It is important to note that the savings associated with this technology are highly dependent on specific locations and the electrical installation or supply situation. Therefore, specific savings cannot be mentioned without considering these factors.

Lower cost related to electricity purchase through the installation of renewable energies

The potential to reduce electricity costs by simply comparing electricity suppliers or hoping for a general cost reduction in the electricity market is limited. However, there is an effective option available to CPOs to invest in their own generation units to partially or fully supply the charging station. This approach reduces dependence on electricity market prices, which is particularly advantageous during periods of rising or high electricity prices.

It is important to note that complete decoupling from the electricity market is uncommon and often not economically viable. In most cases, self-generation units will only supply a portion of the electricity, with the remainder being sourced from the grid.

One viable option, due to its low generation costs, is the combination of a PV plant with charging infrastructure. In some cases, PV modules are installed directly above the charging location, providing roofing, and generating electricity simultaneously.

The overall impact on electricity costs varies depending on factors such as the size of the PV plant, the potential integration of a buffer storage system, and the installed charging power. Examples of successful local combinations can be observed in charging stations operated or planned by CPOs like EnBW (cf. EnBW Energie Baden-Württemberg AG, 2021) and Fastned (cf. Fastned B.V., 2018)(cf. Fastned B.V., 2023).

These examples demonstrate the feasibility of integrating PV systems with charging infrastructure. The specific benefits for a given location will depend on individual circumstances and should be evaluated accordingly. Ideally, such evaluations should be integrated during the planning phase of a charging point. Unlike other measures, it may be challenging (but not impossible) to incorporate or adapt this approach at a later stage.

7.1.2 Income

In addition to cost reduction, increasing revenues can significantly enhance the economic efficiency of charging points. The revenue generated is dependent on two key factors: the price per kilowatt-hour imposed and the total volume of kilowatt-hours recharged over a specific period. Any increase in either parameter will result in higher revenues.

It is crucial to consider the relationship between charging point utilization or the number of recharged kilowatt-hours and the price level when evaluating proposed measures. The subsequent sections will elucidate potential interconnections and the associated risk of unexpected or contrary outcomes compared to the intended goals.

Improved revenues through the implementation of higher prices

The measure of increasing prices may appear straightforward. If a charging point exhibits clear economic inefficiency, the need for higher prices can be easily identified. In some cases, this approach can indeed resolve the issue. However, in other situations, raising the pricing level can lead to reduced utilization and further exacerbate the economic deficit.

To avoid such scenarios, the initial question should examine whether low prices are truly the underlying problem for the charging points. In the case of the evaluated AC charging infrastructure, this can firmly be dismissed since the primary issue lies with the utilization of most deficient charging points. Therefore, imposing higher prices on underutilized AC charging infrastructure would have either no effect or potentially negative consequences for economic efficiency and should be disregarded.

A slightly different scenario emerges for certain assessed DC charging stations. The utilization situation is better in the sense that all charging points have observed charging events. Furthermore, even the most utilized charging point experiences a significant economic deficit.

Consequently, the possibility of implementing higher prices at DC charging infrastructure could be considered. However, it is imperative to concurrently focus on improving utilization levels.

The way of finding the right pricing level and managing the balancing act between price and utilization will be explored in Chapter 7.3.

Improved revenues through higher utilization

As previously mentioned, the primary issue affecting revenues at the assessed AC charging stations is the level of utilization rather than the price imposed. Chapter 7.3 will explore various measures aimed at improving utilization, which is a KPI in itself.

7.2 Potential for improvement regarding the energetic efficiency

This chapter will explain why the KPI energetic efficiency should be improved, define specific goals, and outline concrete measures that can be taken to achieve these goals.

Why should the KPI be optimized and what is its current status?

In an energy trading business, achieving optimal energy efficiency is crucial. A low level of energy efficiency for charging infrastructure for example indicates flaws or inefficiencies within the system or processes, posing a risk to the central business model. On the other hand, an optimized energy efficiency makes the business more sustainable and resilient. Furthermore, an efficient business is better positioned to provide an improved offering to customers.

The analysis conducted in Chapter 6.3 revealed a general lack of data availability for most charging points. However, for the charging points that were assessable, a structural deficit was identified and confirmed for a specific type of charging infrastructure.

Specifically, the DC chargers manufactured by a particular company exhibited high standby consumption due to their unique electrical installation, including the transformer (used at location "DC1"). The high standby consumption resulted in low or critically compromised energy efficiency.

It is worth noting that such issues were not found with AC chargers.

What goals can be formulated for addressing the situation?

In light of the current situation, the following goals have been formulated:

- 1. "Install a comprehensive energy management system for all DC charging locations within the next year, allowing for easy analysis of charging efficiencies."***

The primary objective of this goal is to facilitate the comprehensive application of the designed KPIs for DC charging locations. Due to the economic considerations associated with establishing and operating an energy management system, it was deemed reasonable to exclude AC chargers from this target. Given that no structural issues with energy efficiency were expected for AC chargers, this exclusion is justified.

2. "Improve the energy efficiency of identified underperforming DC charging locations ("DC1") to 90 % or higher within the next year."

This goal aims to address the deficits identified in the present situation. It is imperative to improve the current state of affairs. The target of achieving an energy efficiency of 90 % or higher aligns with the performance levels observed in other assessed charging infrastructure and is therefore attainable. An improvement with the energetic efficiency will hopefully lead to a reduction of operational cost which, in turn, will also benefit the economic goals defined in Chapter 7.1.

Improved energetic efficiency through higher utilization

To achieve the second goal, several possibilities can be considered. One approach is to increase utilization, thereby reducing the significance of standby losses as highlighted in Chapter 6.3.

The underperforming DC charging location "DC1", which consists of four charging points with 350 kW each, was assessed with a standby consumption of around 3 kW (see Table 6-7). With an inadequate capacity utilization averaging at 0.4 %, the resulting energy efficiency was slightly above 60 % (as depicted in Figure 24).

If the capacity utilization of these charging points could be improved to match the average utilization of all assessed DC charging stations (1.1 %), the energy efficiency would increase to over 80 % without making any changes to the 3 kW standby consumption.

Chapter 7.3 will delve into various measures aimed at enhancing utilization, which is a key performance indicator in its own right. By exploring and implementing these measures, it is possible to boost utilization rates and consequently improve the energy efficiency of the charging infrastructure.

Improved energetic efficiency through optimization of the operating time of the location

The other option to increase energy efficiency while maintaining the same utilization is to reduce standby consumption. This can be achieved either by using different hardware, which can be costly, or by adjusting the operating times of the charging location. In the current situation, the charging location "DC1" operates continuously, 24 hours a day.

A detailed analysis reveals that during the entire year 2022, only 18 charging processes took place at said location between 22:00 and 5:00. This accounts for approximately 1 % of the total 1,653 charging events that occurred during that time. In a hypothetical scenario where the location shuts down entirely between 22:00 and 5:00, eliminating standby consumption during those hours, the overall standby consumption would decrease by approximately 30 %. In accordance, the energy efficiency could be increased significantly by about 10 %.

However, it is important to evaluate this approach also in terms of user-friendliness and convenience, as a charging station is typically expected to be available at all times. Balancing the potential energy efficiency gains against user needs and operational considerations is crucial in determining the feasibility of adjusting operating times.

7.3 Potential for improvement regarding the utilization

This chapter will explain why the KPI utilization should be improved, define specific goals, and outline concrete measures that can be taken to achieve these goals.

Why should the KPI be optimized and what is its current status?

Improving utilization can have a positive impact on the economic situation of charging points (as proposed in Chapter 7.1.2) and the energy efficiency (as proposed in Chapter 7.2).

When a charging point is underutilized, it means that it is not being used to its full capacity, resulting in lower revenues and a potential economic deficit. By increasing utilization, more charging sessions can be facilitated, leading to a higher total volume of kilowatt-hours recharged over a given period.

With improved utilization, the charging point can generate increased revenue from a larger number of charging events. This revenue growth helps offset the fixed costs associated with operating and maintaining the charging infrastructure, contributing to improved economic efficiency (see Figure 30).

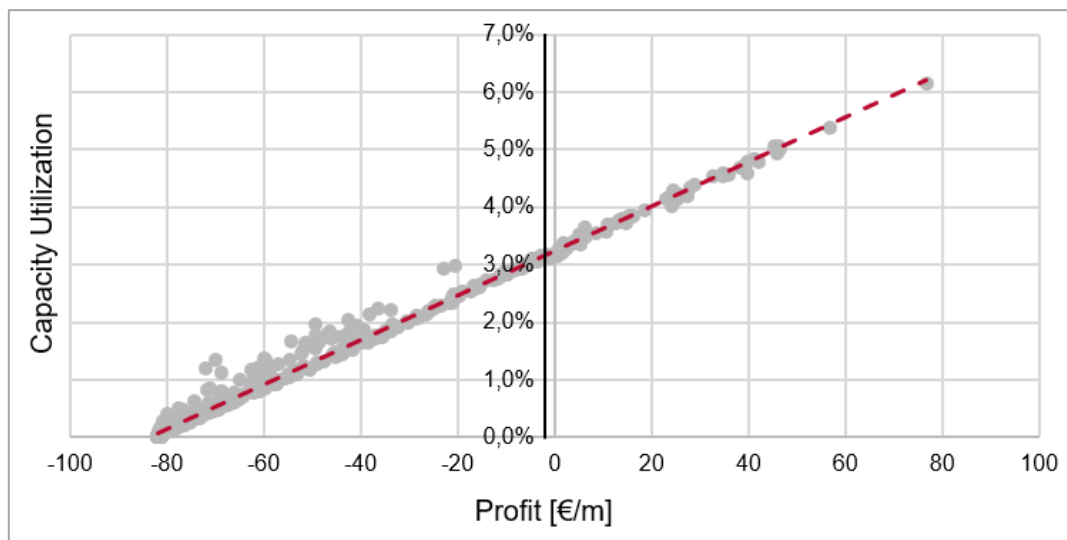


Figure 30 - Correlation of Utilization and Economic Efficiency for AC charging points (own representation)

Furthermore, higher utilization can lead to economies of scale. As more charging sessions occur, the average cost per kilowatt-hour recharged decreases. This is particularly relevant for charging infrastructure with significant fixed costs, such as installation and maintenance expenses. The spreading of these fixed costs across a larger number of charging sessions can help reduce the cost per unit of electricity delivered, improving the profitability of the charging point. The same logic can be followed when talking about standby consumption which was identified as a problem for the energetic efficiency in Chapter 7.2.

In addition to direct revenue benefits, higher utilization can also have indirect positive effects. A charging point that is frequently used attracts more customers, increases brand visibility, and fosters customer loyalty. This can lead to additional revenue streams through partnerships, advertising, or customer loyalty programs.

What goals can be formulated for addressing the situation?

To align with the objective of improving utilization and achieving economic and energy efficiency, the following goals are proposed:

- 1. "Increase the capacity utilization of all assessed AC charging points to achieve an average of 3 % or higher within the next two years."**

Currently, the average capacity utilization of AC chargers is 1.3 %. By raising the bar to 3 % or higher, a level will be reached where the charging points can cover their costs, as outlined in the economic efficiency goal mentioned in Chapter 7.1.

For the DC charging infrastructure, two separate goals need to be considered. The first pertains to economic efficiency:

- 2. "Increase the capacity utilization of all assessed DC charging points to reach an average of 3.4 % or higher within the next two years."**

In addition, there is a condition which is specific to the charging location labeled as "DC1" in the energy efficiency analysis:

- 3. "Ensure that the utilization of the charging location "DC1" is at least at 1.4 %."**

The goal of achieving a 3.4 % capacity utilization is in line with the objective of reducing the overall economic losses of the DC infrastructure by at least 50 %. If the current average utilization of 1.1 % can be increased to 3.4 %, the economic goal will be achieved.

The additional condition for the location "DC1" ensures that the energy efficiency goal is also met. By attaining a capacity utilization of 1.4 % at this specific location, the energy efficiency can be raised to 90 %.

Improved utilization through better assessment of the location and the demand

To effectively address the utilization deficit and achieve the defined goals, a rigorous analysis of the charging station's location and the associated demand situation is an essential first step.

In the context of this thesis and the assessed charging stations, the charging demand primarily originates from the employees' charging needs. However, due to the unavailability of a comprehensive database providing detailed information on the distribution of BEV among the employees and their specific mobility behaviors, approximations were made to estimate the charging demand.

To facilitate an assessment of the charging demand, a thorough examination of the parking situation surrounding the headquarters was conducted. The workplace premises were represented schematically in Figure 31, illustrating various parking decks or areas accessible to the employees. The size of each circle in the Figure corresponds to the number of parking spots available at the respective location, and the number of charging points present is indicated as well.

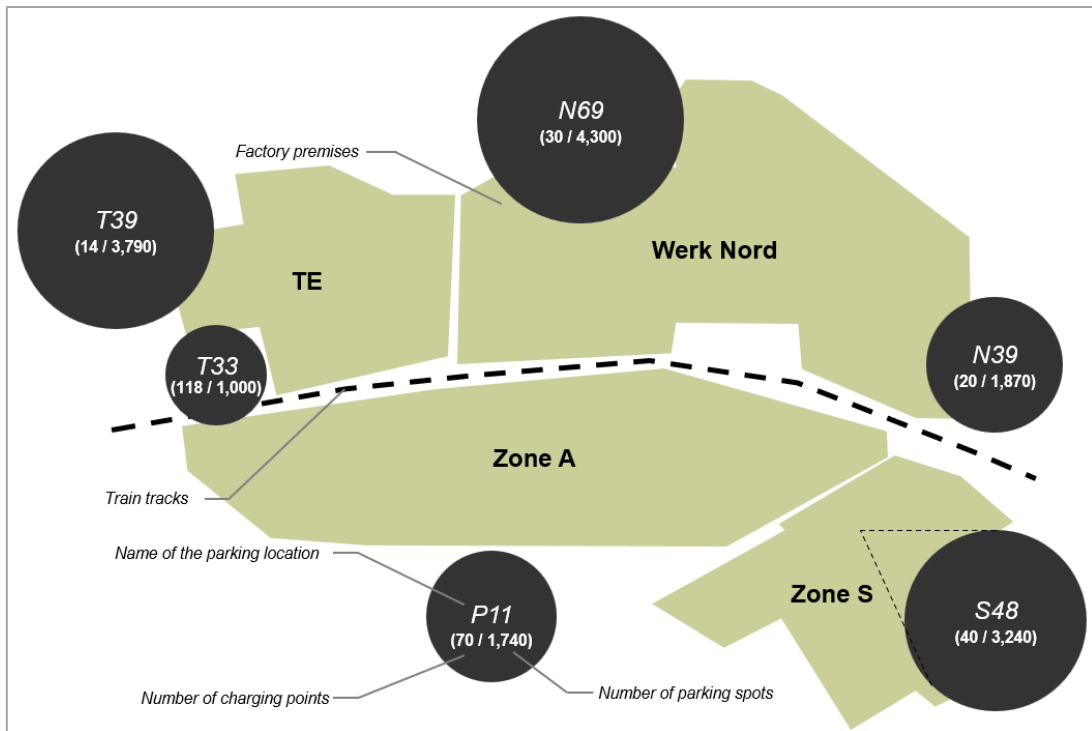


Figure 31 - Schematic representation of AUDI AG headquarters (own representation)

Following, the assumption was made that the charging demand is uniformly distributed across these parking locations, which made an estimation of the charging need become feasible. That means while the sizes of the parking locations and therefore the absolute charging demand may differ, the ratio between BEV and internal combustion engine vehicles was assumed to be uniform at all locations.

For the consecutive analysis (depicted in Figure 32) the demand situation, which was assumed to be correlating with the number of parking spots, is put into relation to the supply, which is the amount of charging points in each location. The ration between both – the share of electrified parking spots – gives an indication about the competitive situation of the charging points and can be compared for every location. Next to that ratio, the assessed asset utilization at each location is given.

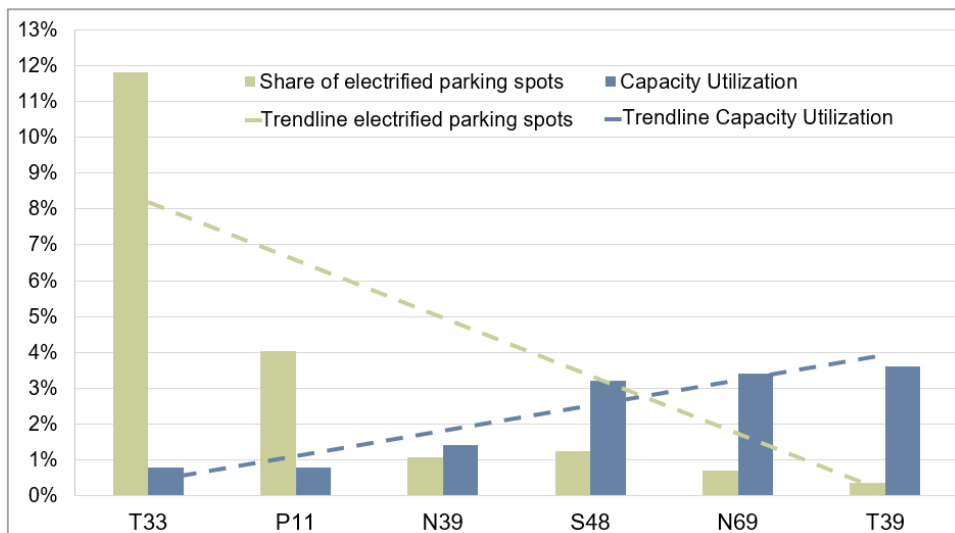


Figure 32 - Share of electrified parking spots against capacity utilization (own representation)

A clear trend can be observed in the data. Starting on the left side a high share of electrified parking spots (12 %) coincides with the lowest capacity utilization (0.8 %). At the other extreme the highest capacity utilization (3.6 %) of all the assessed parking locations (with the use case charge at work) coincides with the lowest electrified parking spot share (0.4 %). The trend between these two extremes is also discernible.

The graph presented and the observed correlation between supply and demand, specifically the share of electrified parking spots and the resulting capacity utilization, provide valuable insights for addressing the previously defined goals.

It is evident from the analysis that the current charging demand at locations *T33* and *P11* exceeds the capacity required, resulting in an average capacity utilization below the target of 3 %. This situation is attributed to the strategic approach taken during the establishment of the charging infrastructure, which aimed to proactively provide charging facilities to employees before the demand fully materialized.

The expectation is that as the share of BEV among employees increases, the demand will eventually align with the existing supply. Consequently, it is proposed to closely monitor the utilization of these stations to assess if the projected rise in demand materializes as anticipated.

In order to gain further insights and address any uncertainties regarding the current situation, conducting more detailed analyses of specific locations can be valuable. To illustrate this point, Figure 33 provides an example of two parking locations that experience low utilization rates. It allows the examination of the utilization distribution across different parking levels.

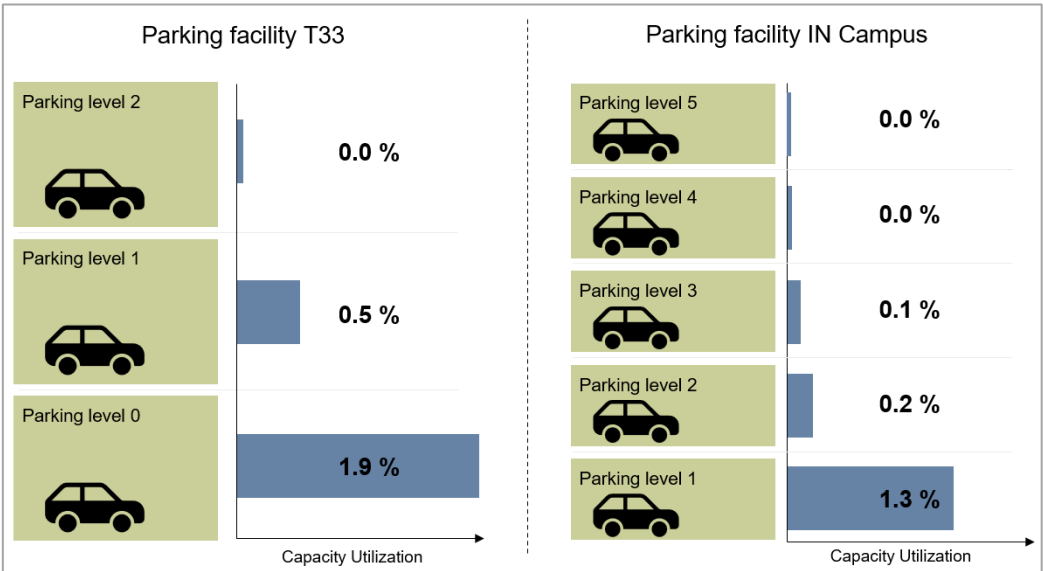


Figure 33 - Utilization of charging point on different parking levels (own representation)

With this additional perspective the supply surplus becomes evident. The charging points located on the lower levels, which are accessed earlier by employees, are sufficient to meet the majority of charging needs. Only in a few instances have employees had to resort to charging

at higher parking decks. In the event that demand matches supply or even if a supply deficit were to occur, a more uniform utilization distribution across the parking levels would be expected.

On the contrary, locations S48, N69, and T39 demonstrate that even with approximately 1 % or fewer electrified parking spots, a capacity utilization of over 3 % can be achieved. However, it is worth noting that these charging locations, on the right side of Figure 32, exhibit a saturation effect. None of the locations reach a capacity utilization of over 4 %, which aligns with the findings from the earlier detailed assessment of individual charging points in Chapter 6.4.

Remarkably, even with the lowest share of electrified parking spots, amounting to 0.4 % at location T39, the capacity utilization stands at 3.6 %, only marginally higher than the utilization at location S48, which has 1.2 % electrified parking spots.

This comparison among the charging locations suggests that there may be unmet charging demand at locations with a lower share of electrified parking spots.

Based on this insight, an upper boundary for a strategic target corridor can be established. If the capacity utilization at a particular location approaches 4 %, further expansion of the charging infrastructure to meet the demand should be considered. Similarly other locations can be categorized regarding their utilization rate (see Figure 34).

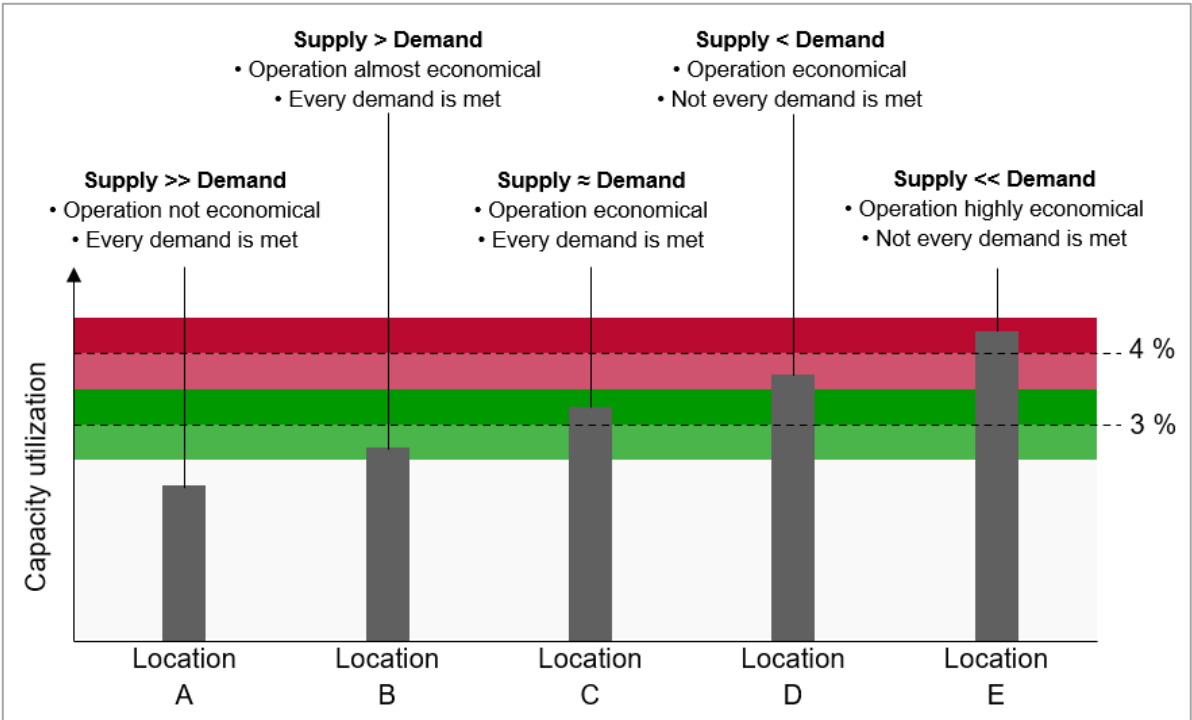


Figure 34 - Strategic target corridor for utilization of charging points (own representation)

The analysis provided above has certain limitations that should be acknowledged. These limitations are as follows:

- The economic assessment given with the different categories is specific to the analyzed location, and it may not represent the optimum for the entire system. Particularly in a

situation where there is high demand at a specific location that is not currently being met by the available supply, the optimum for the location and the optimum for the entire system might differ.

- The target corridor established is specific to the assessed charging points oriented at the charge at work use case, and it may not be applicable to other systems. Different charging systems may have their own unique boundaries and target corridors. For instance, the lower boundary in this case was determined based on economic goals, which in another context may be set different.
- It is important to recognize that the situation and circumstances can change over time. Factors such as changes in demand, advancements in technology, or shifts in user behavior can influence the utilization and economic considerations of the charging infrastructure. Therefore, ongoing monitoring and reassessment are necessary to adapt strategies accordingly.
- An application of the found values as well as a similar analysis for the assessed HPC infrastructure is not feasible in the same manner. Since the initial situation differs from the “charge at work” use case discussed, assumptions for the demand could not be transferred accordingly. The dependencies and complexities associated with HPC charging infrastructure and a regarding demand analysis may require a separate and in-depth analysis, which was not explored in this thesis.

Improved utilization through the implementation of dynamic prices

The adjustment of charging prices, as previously suggested in Chapter 7.1.2 to improve the economic situation, can also be utilized to enhance utilization. Rather than a simple price increase, this proposal focuses on creating price signals that specifically target utilization, and potentially, subsequent economic efficiency.

Price signals have the capacity to create a push or pull effect on demand. In the case of the evaluated charging infrastructure, not only were local utilization deficits identified, but also temporal utilization deficits during night hours and weekends. Implementing a temporal price signal with reduced prices during low-utilization periods could potentially improve the situation.

For example, offering discounted charging rates during off-peak hours, such as late at night or on weekends, may incentivize users to charge their vehicles during these periods, thereby improving overall utilization and potentially optimizing the economic efficiency of the charging infrastructure.

The influence of the proposed measure will have a stronger effect on HPC stations, as charging sessions are more likely to occur during off-peak hours. In contrast, the impact on workplace

charging points may be less significant since employees' charging behavior is primarily driven by their work schedules rather than price incentives.

Another effective measure to influence utilization through pricing signals can be implemented at locations with high utilization and a suspected demand surplus. One approach is to introduce a dynamic price structure that encourages longer active charging sessions compared to the overall standing time of the vehicle.

At "charge at work" charging points, the standing time of the vehicle in front of the station is often significantly longer than the actual charging time. This means that the charging infrastructure is occupied for eight hours a day, but the vehicle only needs three hours to complete its charging.

By implementing the appropriate price signal, longer charging sessions can be initiated. For instance, a pricing model characterized by a decreasing price structure can be employed, where the initial kilowatt-hour costs 40 cents, gradually reducing until the 30 kWh. This descending price pattern serves as an incentive for customers to prolong their charging duration. Instead of engaging in multiple charging events with 15 kWh or less, customers would prefer a single charging session that closely aligns with their standing time in front of the charging station. Consequently, this behavioral shift results in occupying the charging point for an entire day with a charging process that effectively utilizes the available standing time and unblocking it on other days.

However, implementing dynamic price models presents a challenge of creating a tariff structure that is understandable for customers while still encouraging the desired behavior defined by the CPO. Striking the right balance between transparency and incentivizing longer charging sessions is crucial for the success of such pricing strategies.

Improved utilization through user-friendliness or usability measures

Enhancing utilization of charging infrastructure can also be achieved through the implementation of user-friendly and usability measures. These measures, while potentially having a weaker influence on utilization, can still contribute to improving the overall effectiveness of the charging infrastructure. Subsequent Chapters 7.4 and 7.5 will discuss specific measures and explore their potential impact on utilization.

7.4 Potential for improvement regarding the usability

This chapter will explain why the KPI usability should be improved, define specific goals, and outline concrete measures that can be taken to achieve these goals.

Why should the KPI be optimized and what is its current status?

As stated in Chapter 5.4, the KPI usability quantifies the proportion of successful charging processes out of the total charging events at a station. By focusing on improving usability and

reducing flawed charging events, stakeholders can create a positive cycle of user satisfaction, increased utilization, efficient resource allocation, and cost-effectiveness.

For the customer, an enhanced usability improves their overall charging experience and satisfaction, as it reduces obstacles in achieving their goal of recharging energy for their mobility. This positive user experience fosters customer loyalty and encourages repeated usage of the charging points, which in turn contributes to higher utilization rates.

From the perspective of CPOs, improved usability helps optimize resource allocation for charging infrastructure. With a higher proportion of successful charging events, resources such as charging stations and electrical capacity are utilized more effectively. This optimization reduces waste and ensures that the charging infrastructure operates at its maximum efficiency, avoiding underutilization or inefficient allocation of resources.

The correlation between the usability of charging points and their utilization can be observed in Figure 35. It is evident that a high utilization rate does not automatically indicate high usability, as highlighted in the previous chapter where certain locations exhibited a structural supply surplus. However, it is also apparent that achieving a high utilization rate is contingent upon achieving a high level of usability.

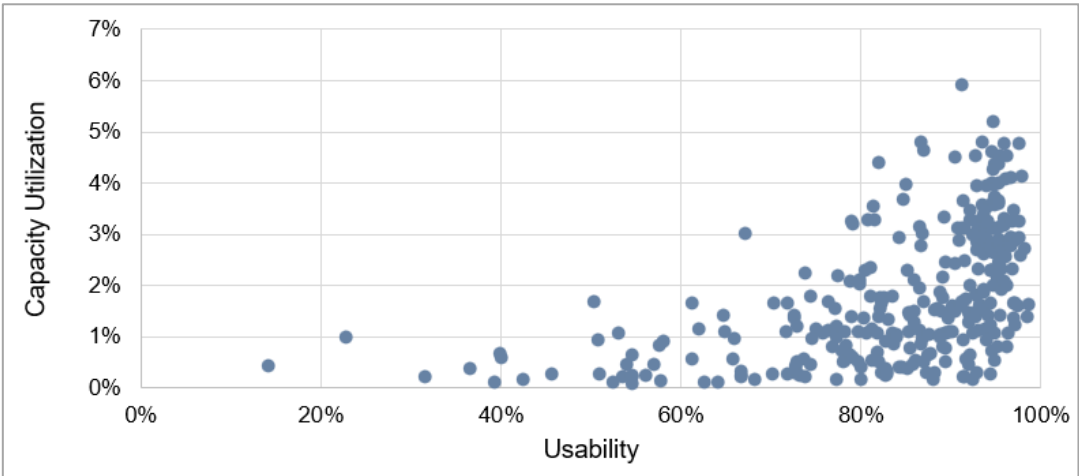


Figure 35 - Correlation between usability and utilization of assessed AC charging points (own representation)

Charging points with a usability below 60 % exhibit an average utilization rate of 0.5 %. Notably, none of these charging points surpasses a utilization rate of 2 %.

In contrast, charging points with a usability of 80 % or higher demonstrate an average capacity utilization of 2.2 %. Among these, a noteworthy 65 charging points achieve a capacity utilization rate of 3 % or higher.

Furthermore, a better usability of charging points helps build trust and confidence among electric vehicle owners. When users consistently have successful charging experiences, it boosts their confidence in relying on the charging infrastructure for their electric vehicles. This trust is crucial for wider adoption of electric vehicles and encourages more users to transition to electric mobility.

What goals can be formulated for addressing the situation?

Based on the analysis conducted in Chapter 6.5, the AC charging infrastructure demonstrates an average usability of 78 %, while the DC infrastructure exhibits a usability of 85.5 %. Building upon the established correlation and considering the current state of the charging infrastructure, the following goals are proposed for improvement:

1. ***"Increase the usability of all assessed charging points to 80 % or higher within the next two years."***
2. ***"Reach an average usability of all assessed AC charging point of 90 % or more within the next two years."***
3. ***"Reach an average usability of all assessed DC charging point of 90 % or more within the next two years."***

The first goal aligns with the utilization goal proposed in Chapter 7.3. Usability is considered a prerequisite for achieving the desired utilization level. By attaining a usability of 80 % or higher, it is expected that a capacity utilization of 3 % or more can be reached, assuming the appropriate demand exists. Conversely, a usability below 80 % is likely to impede the achievement of higher utilization goals.

The second and third goals acknowledge the various benefits associated with improved usability. By aiming for an average usability of 90 % or more for both AC and DC charging points, the intention is to further optimize the charging experience. While a usability of 90 % still allows for a small percentage of unsuccessful charging processes (one out of ten), it demonstrates that this target is reasonable and attainable.

Improved usability through continuous and strategic monitoring

The implementation of a continuous and strategic monitoring combined with proactive maintenance plays a vital role in achieving the previously defined goals. By proactively detecting and addressing these issues, potential disruptions or failures can be minimized.

The analysis resulting from this monitoring approach could highlight charging points with low usability but a high number of charging events. By addressing the repair and maintenance needs of these charging points, the risk of compromising usability over time is mitigated. This proactive maintenance approach helps maintain high levels of usability and prevents potential usability degradation.

Additionally, continuous monitoring and maintenance create a feedback loop that allows for iterative improvements. By closely monitoring the impact of implemented measures, stakeholders can assess their effectiveness and make necessary adjustments. This iterative approach promotes ongoing optimization of the charging infrastructure, leading to incremental improvements in usability and goal attainment over time.

7.5 Potential for improvement regarding the user-friendliness

This chapter will explain why the KPI user-friendliness should be improved, define specific goals, and outline concrete measures that can be taken to achieve these goals.

Why should the KPI be optimized and what is its current status?

Similar to usability an increased user-friendliness enhances the charging experience and customer satisfaction, fostering loyalty and promoting repeated usage of charging points. A smooth and intuitive charging process allows users to effortlessly connect their vehicles, initiate charging, and monitor progress. This streamlined experience saves time, minimizes frustration, and instills confidence in users.

Satisfied users are more inclined to trust and rely on the charging infrastructure for their electric vehicle needs. They may even become advocates for electric mobility, actively encouraging others to utilize charging points, thereby contributing to increased infrastructure utilization.

Improved user-friendliness also offers significant benefits from the perspective of CPOs and service providers. It optimizes utilization, resulting in enhanced overall efficiency. When users can easily comprehend and interact with charging points, their effective utilization is maximized, reducing idle time, and maximizing capacity.

What goals can be formulated for addressing the situation?

Given the user-friendliness analysis in Chapter 6.6, which focused on specific examples to identify challenges and showcase varying degrees of fulfillment and importance across user-friendliness categories, this chapter will also adopt a similar approach. As a result, specific goals for improvement will not be defined, diverging from the previous chapters.

Nevertheless, the following measures will target the identified user-friendliness deficits of the assessed charging infrastructure.

Improved user-friendliness and utilization through better information and signing

One option to improve user-friendliness is by enhancing the information and signage concept for charging stations. The practicality of this improvement is evident, as the most cost-effective and reliable charging option will not be utilized if customers cannot find it or access it.

The survey conducted in Chapter 6.6 revealed that none of the examined charging locations had sufficient signage, which is particularly unfavorable for HPC stations due to their reliance on generating new customers. Therefore, clear, and visible signs indicating the location of charging poles are essential to ensure they are easily found by customers.

Improving user-friendliness goes beyond physical signage and also encompasses the digital aspect of charging locations. Digital offers and applications play a significant role in increasing utilization (cf. Nationale Leitstelle Ladeinfrastruktur, 2020a, p. 61). These digital solutions can

provide clear instructions, real-time information on availability and pricing, user-friendly payment options, and features like reservation systems or notifications.

Improving the accessibility will also help to address utilization deficits, as discussed in Chapter 7.4.

Improved user-friendliness through better readability of controls

Another measure that is related to a deficit which was identified in Chapter 6.6 is ensuring the readability of controls. When the control panel serves as a significant part of the customer journey or is responsible for operating the charging point, it is essential to prioritize readability even in direct sunlight.

Taking measures to protect the controls from direct sunlight or employing design strategies that enhance visibility under such conditions becomes imperative. By ensuring that the controls are readable and easily comprehensible, users can navigate the charging process smoothly and without hindrance.

Improved user-friendliness through transparent pricing

The issue of transparent pricing, which was assessed in Chapter 6.6, arises from the separation between the CPO and the MSP. Currently, not all pricing information is conveyed transparently due to various factors, such as negotiation conditions. As previously mentioned, one challenge is the absence of charging prices displayed at the charging stations themselves. This means that customers must consult their MSP app or refer to their contract to access this information, and in some cases, the CPO may provide the pricing details. The problem lies in the lack of aggregation or consolidation of pricing conditions in one centralized location.

However, there are exceptions to this scenario, with companies like EnBW and Tesla demonstrating a more integrated approach. As both CPO and MSP, they possess knowledge of pricing and conditions, enabling them to display this information in their respective apps, cars and potentially at the charging stations.

Due to the complexity of involving multiple parties, implementing this measure can be more challenging compared to others. The evolution of the public charging market structure, particularly with regard to the role of MSPs, presents an intriguing development that justifies a separate and in-depth analysis.

Improved user-friendliness through charging hardware with connector ports

One important aspect of charging hardware that impacts user-friendliness is the presence of built-in connector ports or fixed charging cables. While some AC charging hardware is already equipped with a charging cable and connector others only provides a standardized socket for EV drivers to connect their own charging cables. (Due to cable diameter requirements, this option is not available for HPC stations.)

Connecting the car with one's own cable may involve additional steps, which can be seen as slightly inconvenient for users.

However, for the CPO, this approach discourages the blocking of charging points. In certain locations, some EV drivers may superficially connect their cars to the station without initiating the charging process. This results in lost opportunities for productive charging sessions for the CPO. Implementing charging infrastructure with ports that require additional cable handling is one measure to prevent this issue.

Furthermore, using private charging cables contributes to a neater appearance. In charging stations without built-in charging ports, the connector and fixed cables are more likely to become dirty or damaged due to direct handling and frequent use. By utilizing charging ports and requiring the use of private cables, these risks can be mitigated.

7.6 Potential for improvement regarding the predictability

Due to the limited knowledge gained during the analysis in Chapter 6.7, specific potential for predictability is difficult to identify. This limitation is attributed to the collaboration with AUDI AG, which provided valuable insights from the perspective of a CPO but lacked extensive knowledge from an energy supplier standpoint. Since this KPI is primarily of interest to grid operators and energy suppliers, further in-depth analysis is required from their perspective in future research or theses.

8 Summary and outlook

The presented thesis provides a comprehensive set of KPIs for assessing public car charging infrastructure. These metrics were derived from stakeholder goals and tailored to various mobility and charging behaviors.

The practicality of the KPIs was demonstrated through a real-world application to an exemplary set of charging points. The analysis provided valuable insights into the assessed infrastructure and identified areas for improvement. Concrete measures were proposed to enhance the performance of the charging points, offering potential benefits that can be applied to other public charging stations. Thus, the research delivers significant added value to the field.

For future applications and adaptations, there are several potential areas to consider.

In this thesis, the focus was specifically on car charging infrastructure for passenger cars, as it is the most developed market for battery electric vehicles. However, as other traffic sectors utilizing the same technology mature and have similar charging needs, it is necessary to reassess and adapt the approach accordingly.

Further expansion of the KPI framework could explore the inclusion of additional metrics such as downtime or planning-oriented KPIs, which can be applied during the planning phase rather than solely during operation. Conducting a location analysis to optimize the placement of charging infrastructure could be a valuable addition.

Additionally, improving or adapting the KPI related to energy efficiency could involve focusing solely on standby power consumption, providing a more specific and accurate assessment.

The developed KPI set can also be applied to other sets of public charging infrastructure, offering insights into their performance, and generating comparative data. This expansion would enhance the overall understanding of charging infrastructure and enable comparability.

Further work could involve monitoring the development of the assessed charging infrastructure and assessing the effectiveness of the proposed improvement measures. This ongoing evaluation would contribute to the continuous enhancement of charging infrastructure.

A more in-depth analysis could focus on specific KPIs, exploring additional measures and evaluating their ease of implementation. For example, a more detailed version of the economic efficiency KPI could include less important factors such as cleaning, repair, and replacement, which were not extensively covered in this thesis.

Moreover, conducting additional in-depth analysis could focus on correlation analysis between different KPIs, such as the relationship between user-friendliness and utilization or the connection between usability and certain infrastructure fabrication. This would uncover additional areas for improvement and generate valuable insights for the public charging sector.

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10 Appendix

User-Friendliness-Checklist

EVSE-ID: [DE'AUC*ETRON*00349](#)

Name: [T33A](#)

Location: [T33A](#)

Phase (AC/DC): [AC](#)

| Obligatory aspects | Source | Fulfilled | Evaluation |
|-------------------------|---|---|------------|
| Charging station design | (cf. Wirkkette Laden Verbundprojekt et al., 2023) | 1. Consistency in the use of EVSE-ID for the identification of the charging connectors. | Yes |
| | | 2. Careful placement of EVSE-ID to preclude mix-ups. | Yes |
| | | 3. Easy identification and readability of controls (like touchscreens on the charging station) with no influence of different weather conditions. | Yes |
| | | 4. Standardization of URLs related to the QR codes which are attached to the charging station, so they are readable by any app. | Yes |
| | | 5. Instruction of all possible ways for authentication on the charging station. | Yes |
| | | 6. High visibility of the service hotline of the CPO on the charging station. | Yes |
| | | 7. Good detectability and clear signage towards and on the charging station (including available charging power). | No |

| Optional aspects | Fulfilled | Evaluation | |
|-------------------------|--|---|-----|
| Charging station design | 8. Acceptance of various forms of payment. | Yes | |
| | 9. Transparent pricing, with display of price per kWh before charging and overall cost after charging. (cf. Wirkkette Laden Verbundprojekt et al., 2023) | No | |
| | Information and Connectivity | 10. Provision of feedback to the customer on the charging process and its action steps. (cf. Wirkkette Laden Verbundprojekt et al., 2023) | Yes |
| | | 11. Implementation of a user-experience concept to facilitate intuitive and easy usability. (cf. Wirkkette Laden Verbundprojekt et al., 2023) | No |
| | 12. Compatibility with mobile apps and navigation systems. | Yes | |
| | 13. Availability of option for direct user-feedback on the charging station. | No | |
| | Safety | 14. Implementation of safety and security measures to protect users and their vehicles. | Yes |
| | | 15. Equipping of charging location with good lighting. | Yes |
| | | 16. Mechanisms for a quick and customized maintenance. | No |
| | Fail-safety | 17. Provision of more than one connector at the charging location. | Yes |
| | | 18. Covering off/Compatibility with different connector types. | Yes |
| | Comfort | 19. Neat appearance of the charging station and implementation of a cleaning concept. | Yes |
| | | 20. Provision of weather protection at the charging station. (cf. Wirkkette Laden Verbundprojekt et al., 2023) | Yes |
| | | 21. Easy cable handling at the charging station. | - |
| | | 22. Reservation of parking spots for BEV only and/or availability of reservation for specific charging time slots. | Yes |
| | Charging location | 23. Barrier-free parking space and easy maneuvering in and out of the parking lot. | No |
| | | 24. Integration of renewable energies at the charging location. | No |
| | | 25. Consideration of the overall environmental impact of the charging infrastructure, including the use of sustainable materials, during the design and setup of the charging location. | No |
| | | 26. Integration with other services (like restaurants, shops, or restrooms). | No |

User-Friendliness-Checklist

Date: 10.05.23

EVSE-ID: [DE*AUUC*EIRON*00150](#)

Name: [P11](#)

Location: [P11](#)

Phase (AC/DC): [AC](#)

| Obligatory aspects | | Source | Fulfilled | Evaluation |
|-------------------------|---|---|-----------|---|
| Charging station design | 1. Consistency in the use of EVSE-ID for the identification of the charging connectors. | (cf. Wirkkette Laden Verbundprojekt et al., 2023) | Yes | - |
| | 2. Careful placement of EVSE-ID to preclude mix-ups. | | Yes | Placed right above the charging port. |
| | 3. Easy identification and readability of controls (like touchscreens on the charging station) with no influence of different weather conditions. | | Yes | Readability is good, but the station has two screens. One for the control and one for the energy meter which is irritating. |
| | 4. Standardization of URLs related to the QR codes which are attached to the charging station, so they are readable by any app. | | Yes | The QR-Codes are readable by any App, but there are three different QR Code on the station which can irritate the customer. |
| | 5. Instruction of all possible ways for authentication on the charging station. | | Yes | Instructions are good and clear but could be more present. |
| | 6. High visibility of the service hotline of the CPO on the charging station. | | Yes | |
| | 7. Good detectability and clear signage towards and on the charging station (including available charging power). | | No | Charging station is only detectable from near. No signage to facilitate finding from afar. (But charge at work use case.) |
| Charging location | | | | |
| Optional aspects | | Source | Fulfilled | Evaluation |
| Charging station design | 8. Acceptance of various forms of payment. | (cf. Wirkkette Laden Verbundprojekt et al., 2023) | Yes | Ad-hoc (Master Card, Visa Card, PayPal), RFID (MSP Card) |
| | 9. Transparent pricing, with display of price per kWh before charging and overall cost after charging. (cf. Wirkkette Laden Verbundprojekt et al., 2023) | | No | Ad-hoc: yes; MSP: no |
| | 10. Provision of feedback to the customer on the charging process and its action steps. (cf. Wirkkette Laden Verbundprojekt et al., 2023) | | Yes | - |
| | 11. Implementation of a user-experience concept to facilitate intuitive and easy usability. (cf. Wirkkette Laden Verbundprojekt et al., 2023) | | No | No feedback for the order of necessary actions to start the charging process. |
| | 12. Compatibility with mobile apps and navigation systems. | | Yes | - |
| | 13. Availability of option for direct user-feedback on the charging station. | | No | - |
| | 14. Implementation of safety and security measures to protect users and their vehicles. | | Yes | Regarding the standard. |
| | 15. Equipping of charging location with good lighting. | | Yes | - |
| | 16. Mechanisms for a quick and customized maintenance. | | No | - |
| | 17. Provision of more than one connector at the charging location. | | Yes | - |
| | 18. Covering off/Compatibility with different connector types. | | No | - |
| | 19. Neat appearance of the charging station and implementation of a cleaning concept. | | Yes | - |
| | 20. Provision of weather protection at the charging station. (cf. Wirkkette Laden Verbundprojekt et al., 2023) | | No | - |
| | 21. Easy cable handling at the charging station. | | Yes | - |
| | 22. Reservation of parking spots for BEV only and/or availability of reservation for specific charging time slots. | | Yes | - |
| | 23. Barrier-free parking space and easy maneuvering in and out of the parking lot. | | No | The parking spot is dimensioned generously, but the charging station itself is placed on a curb. |
| | 24. Integration of renewable energies at the charging location. | | No | - |
| | 25. Consideration of the overall environmental impact of the charging infrastructure, including the use of sustainable materials, during the design and setup of the charging location. | | No | - |
| | 26. Integration with other services (like restaurants, shops, or restrooms). | | No | Not applicable. |

User-Friendliness-Checklist

Date: 26.04.23

EVSE-ID: [DE*AUC*E02*H0001*4](#) Name: [Porsche HPC Forum](#)

Location: [Forum Ingolstadt](#) Phase (AC/DC): [DC](#)

| Obligatory aspects | Source | Fulfilled | Evaluation |
|-------------------------|---|-----------|--|
| Charging station design | (cf. Wirkkette Laden Verbundprojekt et al., 2023) | No | EVSE-ID is displayed different on screen and label. |
| | | Yes | - |
| | | Yes | Readability of touchscreen is difficult in direct sunlight. |
| | | Yes | |
| | | Yes | Instructions are displayed, but for one option of authentication the instruction is given on the touchscreen and for the other it is given on a label. |
| | | Yes | |
| | | No | Charging station is only detectable from near. No signage to facilitate finding from afar. |
| Charging location | - | | |

| Optional aspects | Fulfilled | Evaluation | |
|-------------------------|-------------------|--|--|
| Charging station design | Yes | Ad-hoc (Master Card, Visa Card, PayPal), RFID (MSP Card) | |
| | No | The respective price is only displayed (on a Smartphone) for ad-hoc charging. | |
| | Yes | - | |
| | Yes | The displayed information on the screen and light signals facilitate the user-experience. Nevertheless, additional features could improve the situation. | |
| | Yes | - | |
| | No | - | |
| | Yes | Regarding the standard. | |
| | Yes | Lighting is included in the charging station itself. | |
| | No | - | |
| | Yes | - | |
| | No | Only CCS2 connectors. | |
| | Yes | The overall appearance is neat, but some traces of usage can be seen at the white connector for example. | |
| | No | - | |
| | Yes | The weight to be lifted is lower than 5 kg. | |
| | Yes | - | |
| | No | The parking spot itself is dimensioned generously, but the charging station itself is placed on a curb. | |
| | No | - | |
| | No | - | |
| | Yes | Restaurant and toilets are within reach. | |
| | Charging location | Yes | Restaurant and toilets are within reach. |
| | | No | |
| | | No | |
| | | No | |
| | | No | |
| | | Yes | |