

Article

Simulation-Based Tool for Strategic and Technical Planning of Truck Charging Parks at Highway Sites

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Abstract: In the forthcoming years, it is expected that there will be a notable increase in the market penetration of electrically powered trucks with the objective of reducing greenhouse gas emissions in the transport sector. It is therefore essential to implement a comprehensive public charging infrastructure along highways in the medium term, enabling vehicles to be charged overnight or during driving breaks, particularly in the context of long-distance transportation. This paper presents a simulation model that supports the planning and technical design of truck charging parks at German highway rest areas. It also presents a transferable mobility model for the volume of trucks and the parking times of long-distance trucks at rest areas. Subsequently, a simulation is offered for the purpose of designing the charging infrastructure and analysing peak loads in the local energy system. The potential of the models is demonstrated using various charging infrastructure scenarios for an exemplary reference site. Subsequently, the extent to which the charging infrastructure requirements and the service quality at the location depend on external conditions is explained. In addition, the influence of the range of offers and the business models on the efficiency of infrastructure use is established. Based on the findings, general recommendations for the design of truck charging parks at rest areas are then given and discussed.

Keywords: battery electric truck; megawatt charging; truck charging park; rest area



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1. Introduction

In 2021, the European Union (EU) made a commitment to achieve complete climate neutrality by 2050, with the objective of limiting the negative effects of climate change [1]. This signifies the necessity of a substantial decrease in greenhouse gas emissions across all sectors by 2030. In the transport sector, this is being accompanied by the introduction of regulatory measures in the form of ambitious targets for CO₂ emissions from the vehicle fleets of individual manufacturers sold in the EU [2]. This is leading to an increasing substitution of combustion engines with alternative drive technologies. In regard to heavy-duty vehicles, manufacturers are predicting that electric-powered vehicles will account for over 50 percent of the market in Germany by 2030 [3]. For use in long-distance transport, regular charging of the batteries is necessary due to the high mileage of these vehicles. Some of these charges can be handled at the depots where the vehicles park overnight. In particular, a public charging infrastructure along the highways is essential for multi-day trips. It is recommended that charging take place during legally required break and rest periods, during which the vehicles can be parked at rest areas or truck stops.

Nevertheless, the establishment of an adequate charging infrastructure is associated with a considerable level of effort and necessitates extended lead times. This is due to the fact that the higher-level grid infrastructure usually also has to be upgraded in order to provide the required grid connection. The planning, design and dimensioning of the necessary truck charging parks must take into account major uncertainties regarding future requirements and boundary conditions, since there are currently practically no heavy-duty electric trucks in use [4]. The question arises as to which battery sizes and charging

capacities can be expected in the future. To what extent should the offers be designed to have minimal impact on logistics processes? It is necessary to determine the level at which peak loads and energy sales are to be expected at the respective locations. This work presents a simulation model that supports the strategic and technical planning of truck charging infrastructure at rest areas. The investigation of the effects of various boundary conditions and designs of individual truck charging parks is presented using a scenario-based approach, which includes the presentation of options for action. The potential of the tool and the charging infrastructure concepts derived from it are demonstrated using a reference rest area on a German highway.

2. State of Science and Technology

Heavy-duty trucks and buses are responsible for 25 percent of CO₂ emissions in the transport sector and for six percent of total CO₂ emissions in the EU [2]. In 2019, binding reduction targets were set for truck manufacturers for trucks with a gross vehicle weight of over 16 tonnes with the objective of reducing emissions in this segment [2]. With 2019 as the reference year, the emissions of the vehicle fleets of the individual manufacturers sold in the EU must be reduced by 15 percent by 2025 and by 30 percent by 2030. The limits are currently being tightened further, with the objective of achieving a reduction of 45 percent from 2030, 65 percent from 2035 and 90 percent from 2040 [5,6]. In order to comply with these limits, there is a need for a significant and rapid market expansion of alternative-fuelled trucks.

In addition to hydrogen-based technologies, purely electric drives are also considered to have significant potential for application in long-distance transport [7]. As of 1 October 2023, there were approximately 76,000 electric trucks registered in Germany, representing a market share of 2.0 percent. However, these are predominantly the lighter commercial vehicles, though larger vehicles are also increasingly being registered for regional transport [4]. The number of semi-trailer trucks, which are more relevant for long-distance transport, was just 224 units, which corresponds to a share of 0.1 percent. This is partly due to the facts that there are currently only a limited number of heavy-duty electric trucks available on the market and that the market launch of semi-trailer trucks for long-distance transport is only just beginning [8]. Nevertheless, vehicle manufacturers have already predicted sales of 57,800 battery-powered heavy-duty trucks (N3, >12t) by 2030, which would correspond to a market share of approximately 57 percent [3]. Long-haul electric semi-trailer trucks, which are already available or will be coming onto the market soon, have usable battery sizes in the range of 400 to 900 kWh with ranges between 300 and 800 km [9–14]. In practice, consumption values of up to 1.1 kWh/km have been achieved, which is in line with the manufacturers' range forecasts for this vehicle class [9,14]. These forecasts indicate that by 2025, the range will be 350 to 650 km, by 2027, it will be 450 to 800 km, and by 2030, it will be 600 to 1000 km [3].

The availability of public charging infrastructure, particularly along highways and long-distance roads, is an essential requirement for the use of electric trucks in long-distance transport. The minimum requirements for such infrastructure were set by the EU in 2023 in the Alternative Fuels Infrastructure Regulation (AFIR) [15]. By the end of 2030, the development of a minimum of two charging points (CPs), each with a capacity of at least 350 kW for trucks, must be ensured on the main transport axes at intervals of no more than 60 km. A charging infrastructure with a total charging capacity of at least 3600 kW must be provided at these sites. Furthermore, binding interim targets have been set for 2025 and 2027. Currently, the charging infrastructure for trucks on European long-distance routes is almost non-existent. However, the first truck charging parks have recently been opened in the Netherlands [16–18].

For example, electric trucks can be charged during mandatory driving breaks. The breaks and rest periods are regulated by the legal working time and break regulations for truck drivers according to the German Drivers Act [19,20]. The latter distinguishes between a 45 min break after a driving time of 4.5 h, a rest period of 9 to 11 h after a daily

driving time of 9 h, and a weekly rest period of 45 h. In particular, the longer rest periods can be used to charge overnight with a Night Charging System (NCS) with moderate charging power. The 45 min breaks are suitable for intermediate charging with a higher power output.

In Europe, the Combined Charging System (CCS) is generally used for direct current (DC) truck charging. This system is already established for high-power charging of passenger cars with charging capacities of up to several hundred kilowatts [21]. The CCS standard can also be used with lower power levels as an NCS. The Megawatt Charging System (MCS) was designed for even higher charging capacities and is expected to be standardised in 2025 for charging capacities of up to 3.75 MW [22]. MCS charging stations and compatible vehicles with charging capacities in the 1 MW range are currently being developed and demonstrated by several manufacturers [23–25]. The aim is to establish market-ready systems in Germany as part of the cross-manufacturer HoLa project, which will be in practical operation under everyday conditions from the end of 2024 [26]. Furthermore, research is already being conducted on systems with charging capacities of up to 3 MW on a test stand as part of the NEFTON project [27].

The demand for public truck charging infrastructure in Germany and Europe has been the subject of analysis in several studies. In the studies ‘Public fast charging infrastructure for battery electric trucks—a model-based network for Germany’ [28] and ‘Where to Charge Electric Trucks in Europe—Modelling a Charging Infrastructure Network’ [29], a top-down approach is taken for an MCS charging infrastructure. In this approach, the frequency of public charging events for electric heavy-duty trucks is initially estimated based on the annual traffic volume in the region under consideration. These charging events are then assigned to potential charging locations at 50 or 100 km intervals and distributed according to the traffic volume of passing trucks during the day. The number of MCS CPs required per location is then calculated using a queueing model, assuming an average waiting time of less than five minutes. The scenarios for an MCS charging network in Germany with 15 percent e-trucks in the fleet are modelled for 2030 [28]. The methodology is applied to a European perspective with 5 and 15 percent electric trucks for the years 2025 and 2030, respectively [29].

In the study entitled ‘Long-Distance Electric Truck Traffic: Analysis, Modelling and Designing a Demand-Oriented Charging Network for Germany’, the volume of truck traffic in Germany was modelled using an agent-based simulation, and the demand for an MCS charging network was derived [30]. The model is based on studies of freight traffic between source and destination points in Germany and Europe [31]. All truck journeys with a total distance of over 300 km and a start or end point in Germany are considered, with electrification shares of 1 to 20 percent. For the purpose of modelling intermediate charging of e-trucks using MCS, existing locations near highways that already have petrol stations or a charging infrastructure are considered.

The study ‘StratES—Scenarios for the Electrification of Road Freight Transport’ focuses on an economic comparison of different alternative drive systems for trucks, including infrastructure costs [32]. In order to ascertain the requisite charging infrastructure for electric trucks in Germany, driving profiles from the German mobility study entitled ‘Motor vehicles in Germany 2010’ [33] were used. The selection of an appropriate charging option is dependent upon the specific routes driven and economic and time efficiency considerations. The total energy demands for public charging resulting from the model are then distributed to locations at 60 km intervals along the highways. Additionally, the local energy demands are also transferred into a daily profile corresponding to the volume of passing trucks. The peak times then define the local charging infrastructure demand for CCS and MCS. In contrast to the previous studies, no electrification quota is specified. Instead, this is determined through a market ramp-up model that considers the economic boundary conditions in different scenarios.

As part of the study of ‘Grid-related challenges of high-power and megawatt charging stations for battery-electric long-haul trucks’, the objective is to analyse the grid integration

of (semi-)public truck charging parks at highways and logistics locations in Germany [34]. In contrast to the previous studies, this research explicitly considers specific reference locations, including their design, grid connections and local infrastructure costs. The capacity utilisation is contingent upon the volume of traffic at the location, the proportion of electric trucks on the road between 2027 and 2040 and the general availability of charging infrastructure, which is assumed to be every 50 to 200 km. The number of trucks arriving during the course of the day is modelled stochastically based on distributions for mobility behaviour [33] and manual counts at real rest areas [35]. In order to reduce the peak load, scenarios with charging management for the entire site and a battery storage system are also considered.

The study conducted by the German National Centre for Charging Infrastructure (NLL), entitled ‘Easy charging at service areas: Design of the network connection for e-truck charging hubs’ [36], is based on the same methodology as the study just described [34], but with adapted boundary conditions. Three reference locations with different traffic volumes in Germany are defined. In addition to MCS charging and public night charging, a simple model for passenger car charging at the rest areas under consideration is also taken into account. The share of electric trucks is set at 7.5, 20 and 50 percent. This work focuses on the technical, organisational and economic challenges associated with the provision and scaling of demand-oriented grid connections.

In the article ‘Fast-charging hubs for e-trucks in Switzerland’ [37], the future demand for MCS CPs for e-trucks in Switzerland is estimated. This estimation is based on a synthesis of national freight transport statistics [38], toll data from the performance-related heavy vehicle charge [39] and insights derived from workshops and surveys on future charging behaviour.

The studies described are often based on a top-down approach, in which the charging infrastructure requirement is derived from the total European or national traffic volume [28–30,32,37]. Another approach is to consider the traffic volume at an exemplary location, with a focus on peak loads and grid connection [34,36]. Consequently, the focus of the investigations is on the pure demand for CPs for an overall charging network or individual locations. The strategic planning of individual truck charging parks at specific locations, taking into account the local traffic situation, the space available at the location and possible business models for the services offered, is rarely explicitly considered. Furthermore, the studies do not address the impact that the design of a charging infrastructure and the associated business models have on the quality of service at the location and how the boundary conditions affect the handling of charging requirements at the location. The objective of this study is to address the mentioned gap with a bottom-up approach, based on the individual truck traffic at specific rest areas. A transferable planning tool for individual locations with a high temporal resolution is introduced. In addition to a technical analysis of infrastructure requirements, this tool enables strategic planning of the offer and business models. The tool is based on modelling the mobility and parking behaviour of trucks at rest areas. The complete description of these behaviours requires the availability of a data set that maps the temporal and spatial usage behaviour in its entirety. In order to gain a comprehensive understanding of the utilisation of rest areas and to close the relevant data gap, several dynamic traffic and parking data sets are recorded and combined.

3. Data and Methodology

The bottom-up simulation tool, developed as part of this work, comprises two main parts, which are described in Sections 3.1 and 3.2: a transferable, site-specific mobility model for long-distance heavy-duty trucks at highway rest areas, and the simulation of a charging infrastructure for truck charging parks at the locations under consideration. To demonstrate the functionalities of the tool and to derive general findings, various charging scenarios for a reference location are defined in Section 3.3.

3.1. Mobility Model

The mobility model is used to generate the input data for the simulation of the charging infrastructure. In order to achieve this, a simulation of the truck arrivals at a highway rest area over the course of a day was carried out in minute resolution for one year. Only heavy-duty trucks and semi-trailer trucks that arrived at the rest area for a legally required break, rest or weekly rest were included in the analysis. The assignment of the three options to an incoming vehicle was carried out by using a probability distribution, the parameters of which were derived from the weekday and the time of day. In this context, a differentiation was made between working days from Monday to Friday, Saturdays, Sundays and public holidays. The assumption that the mobility behaviour at the rest area will not change significantly because of the electrification of the vehicles formed the basis of the present study.

The definition of the relevant factors to the mobility model was primarily based on transport processes and legal requirements regarding rest periods. Three data sets are used in the location-specific mobility model to describe the temporal and spatial behaviour of trucks: the capacity utilisation of the rest areas, a probability distribution of the rest periods and the origin–destination traffic.

3.1.1. Time Attendance Profile

The determination of the capacity utilisation of rest areas and the calculation of arrival times were determined with the help of dynamic occupancy data, which were collected at 20 rest areas in Bavaria, Hesse and Rhineland-Palatinate in Germany [40]. The data collection was conducted via an online interface and was executed every minute over a period of several months. The occupancy data revealed that the parking capacities of the rest areas were frequently and significantly exceeded at night due to trucks parking in areas that officially exceed the available parking spaces. Figure 1 illustrates the average and standard deviation of the weekly occupancy of truck parking spaces, based on the collected data. The curve depicts the typical occupancy patterns over the course of a week, with the grey area representing the fluctuations around the mean.

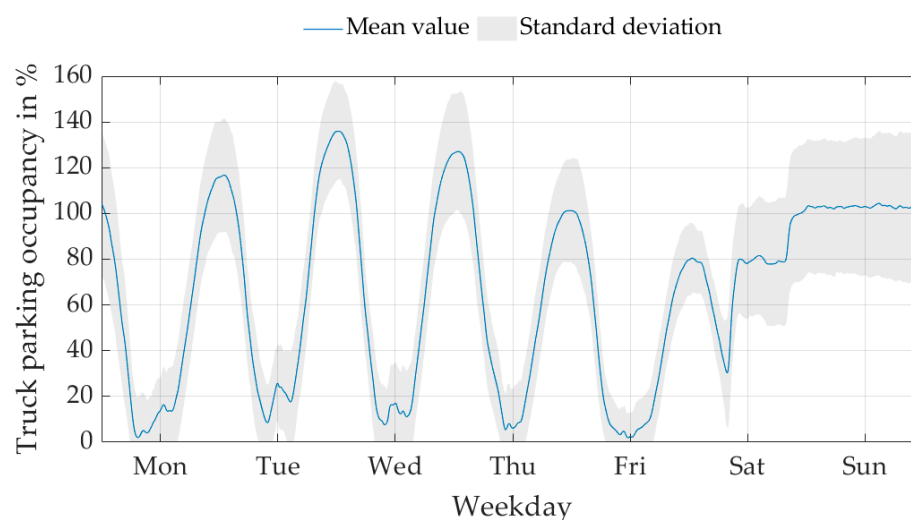


Figure 1. Parking occupancy of 20 German rest areas over the course of a week.

The occupancy data provided information about the capacity utilisation of the rest areas. The parking occupancy can be extrapolated to other rest area locations using a multimodal time series analysis based on road utilisation [41,42]. This hybrid approach integrates three essential analytical components: time delays, cluster analysis and negative regression. The result is a differentiated and precise modelling of the dynamic relationship between road utilisation and parking occupancy.

The occupancy level of truck parking areas $p(t)$ at a given time t is modelled as a function of the preceding road utilisation $s(t - \tau)$.

$$p(t) = f(s(t - \tau)) \quad (1)$$

Changes in road utilisation have a delayed effect on parking occupancy. The time lag τ is used to capture this effect. The temporal road utilisation $s(t)$ is provided by the automatic permanent counting stations on highways, which enable a permanent count of all motor vehicles. The nearest automatic permanent counting station is assigned to the rest area, and the counts for semi-trailers are used for the investigations.

The time periods and data are divided into specific clusters representing the different periods within the week. For a weekly forecast, there are four specific clusters:

- Weekday Day (WD-D): Monday through Friday, 7 AM to 4 PM;
- Weekday Night (WD-N): Monday through Friday, outside of 7 AM to 4 PM;
- Saturday (SAT): 7 AM to 23:59 PM;
- Sunday (SUN) and Holidays.

For each of the clusters, a separate regression model is specified that describes the time-delayed relationship between road utilisation and parking occupancy. In this case, an appropriate functional form $f_{Cluster}$ is fitted specifically for each cluster, while the parameters of the model represent $\beta_{Cluster}$ [41,42]. The inverse relationship between road utilisation and parking occupancy results in negative regression parameters $\beta_{Cluster} < 0$.

$$p(t) = \begin{cases} f_{WD-D}(s(t - \tau)), \beta_{WD-D} & \text{for } WD - D \\ f_{WD-N}(s(t - \tau)), \beta_{WD-N} & \text{for } WD - N \\ f_{SAT}(s(t - \tau)), \beta_{SAT} & \text{for } SAT \\ f_{SUN}(s(t - \tau)), \beta_{SUN} & \text{for } SUN \end{cases} \quad (2)$$

The absolute number of trucks $R(t)$ at a given time t at a rest area with a total capacity C is proportional to the parking occupancy level $p(t)$ in percent:

$$R(t) = p(t) \times \frac{C}{100} \quad (3)$$

The determination of the parking times of incoming trucks at the rest areas, which are used as the time for charging the truck battery, is determined by modelling synthetic trip chains [43]. The synthetic trip chains are based on historical driving profiles, which were collected as part of the mobility study ‘Motor vehicles in Germany 2010’ [31]. The modelling of the parking times of the trucks at the rest areas is based on the legal working hours and break regulations for truck drivers according to the German Drivers Act [20]. The modelled break regulation differentiates between a 45 min break after a driving time of 4.5 h, a 9–11 h rest period after a daily driving time of 9 h, and a weekly rest period of 45 h. The probability of an arriving truck taking one of the break types on weekdays, Saturdays and Sundays is determined from the synthetic trip chains of the trucks over a year based on the historical trip profiles. The functions of the time distribution and the probability of the break regulation as a function of time and day are derived from the synthetic trip chains. As soon as a vehicle i arrives at a time θ_i , it is parked for a certain period of time T , which is distributed according to a conditional probability distribution $G(T|\theta_i)$.

$$G(T|\theta_i) = \begin{cases} g_{Break}(\theta_i) & \text{for } T = 45 \text{ min} \\ g_{Rest}(\theta_i) & \text{for } T \in \{9 \text{ h}, 11 \text{ h}\} \\ g_{WeeklyRest}(\theta_i) & \text{for } T = 45 \text{ h} \end{cases} \quad (4)$$

Figure 2 shows the probability distribution for the occurrence of the three modelled break patterns—break time, rest period and weekly rest—on weekdays, Saturdays and Sundays. The graphs illustrate the change in the probability of each type of break over the course of the day. There are significant differences between weekdays, Saturdays and

Sundays. These differences particularly affect the frequency of break times on weekdays, the distribution of rest periods on Saturdays and the dominant break time on Sundays. The latter is due to the driving ban on Sundays.

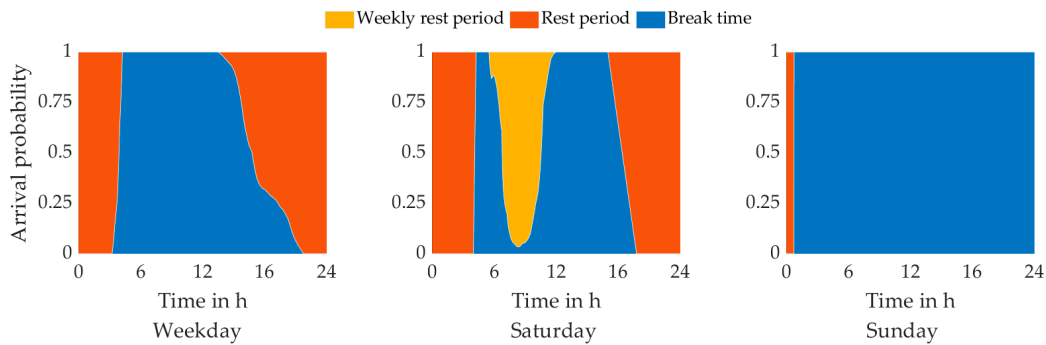


Figure 2. Probability for the break type/parking time for arriving trucks.

The number of trucks $R(t)$ in the car park at a given time t is represented by the sum of all incoming trucks, which are still in the car park at that time t .

$$R(t) = \sum_i S_i(\theta_i) \cdot \mathbf{1}_{\{T_i > t - \theta_i\}} \text{ where } T_i \sim G(T|\theta_i) \quad (5)$$

The consideration of the truck S_i , which arrived at the time θ_i , is based on the parking time T_i according to the following formula:

$$S_i(\theta_i) = \frac{R(t)}{\sum_i \mathbf{1}_{\{T_i > t - \theta_i\}}} \text{ where } T_i \sim G(T|\theta_i) \quad (6)$$

The arrival rate $\lambda(t)$ at a given time t describes the difference in the number of trucks in the parking area between two consecutive time intervals. The arrival rate depends on whether the truck i was already in the parking area at the time of the previous time interval $t - \Delta t$.

$$\lambda(t) = \sum_i S_i(\theta_i) \cdot [\mathbf{1}_{\{T_i > t - \theta_i\}} - \mathbf{1}_{\{T_i > t - \Delta t - \theta_i\}}] \quad (7)$$

$\lambda(t)$ represents the number of trucks arriving at the rest area under consideration in the subsequent simulation steps.

3.1.2. Driving Profile

In addition to the temporal assignment of arrival time and duration of stay, the previously travelled and upcoming distances are matched to the parked truck in order to determine the energy demand. In order to ensure the transferability of the methodology to other sites and to take into account international traffic and the direction of travel of the trucks, a data set with synthetic traffic flows [44,45] of European road freight transport with origin–destination traffic is used. The resulting aggregated truck traffic flows of the synthetic traffic flows are based on ETISplus data [46,47] and Eurostat data [48] for truck traffic volumes in Europe. The origin–destination traffic describes the traffic flows with the number of trucks per year between NUTS3 regions; thus, regional trips within the individual NUTS3 region are not considered. In order to scale the traffic flows to the year 2022, the growth rates for the international traffic flows based on the country-specific export growth factor are used [44]. The origin–destination traffic includes the individual waypoints $w_1, w_2, \dots, w_n$ along the main European transport axes [49] between the source node k and the target node m . The driving distances of the passing or arriving trucks at the considered rest area result from the assignment of the nearest waypoint r of the origin–destination matrix. The calculation of the driving distances is carried out using the Dijkstra algorithm

to determine the shortest paths. The entire path $q(k, m)$ contains waypoints $w_1, w_2, \dots, w_n$ with the source node k and the target node m .

$$q(k, m) = q(k, w_1) + q(w_1, w_2) + \dots + q(w_{n-1}, w_n) + q(w_n, m) \quad (8)$$

The total distance of the route D_{total} is given by the sum of the distances of all the sections, with $w_0 = k$ and $w_{n+1} = m$. The distance from the starting point to the observed waypoint r is called $D_{pre,r}$, and the subsequent distance to the destination point is labelled $D_{post,r}$. The observed waypoint r is positioned on the path $q(k, m)$ between the waypoint w_j and w_{j+1} . The total distance D_{total} , which includes the distances preceding and following the observed waypoint r , is determined by the sum of the path lengths $d(w_i, w_{i+1})$ between two consecutive waypoints.

$$D_{total} = D_{pre,r} + D_{post,r} = \left(\sum_{i=0}^j d(w_i, w_{i+1}) \right) + \left(\sum_{i=j+1}^n d(w_i, w_{i+1}) \right) \quad (9)$$

Based on the determined frequency distribution of the driven distances of the trucks, an assignment of the driven distances to the arriving trucks is carried out. The minimum driving distance $D_{pre,r}$ for the route to the observed waypoint r for a potential parking manoeuvre is calculated from the maximum driving time of 4.5 h at an average speed of 70 km/h, resulting in a value of $D_{pre,r} > 315$ km. Trips with shorter $D_{pre,r}$ were excluded from the assignment to parking trucks.

The number of trucks arriving at the site in minute resolution over the course of a year, the probability distributions for the individual assignment of the reason for the stay (break time, rest or weekly rest) and the distribution of the driving routes of the arriving vehicles are transferred as input data for the subsequent simulation of the truck charging park at the location under consideration.

3.2. Charging Infrastructure Model

The input data from the mobility model provide the basis for simulating the charging events at a truck charging park at the observed rest area on the highway over a period of one year. In this framework, individual characteristics are attributed to the arriving trucks, with these characteristics varying in different scenarios. Moreover, the design of the charging infrastructure at the truck charging park is defined, particularly with regard to the number of CPs and their maximum charging power. The simulation can be used to analyse a number of relevant factors, including the load flows, peak loads and energy demand, as well as the service quality at the site in terms of capacity utilisation and waiting, parking and charging times. These analyses can be carried out depending on the previously defined boundary conditions. Figure 3 provides an overview of the simulation model for charging trucks at a rest area and shows how the charging strategy depends on the duration of the stop. Battery-electric trucks (BETs) with a specific state of charge (SOC) can be charged overnight via an NCS or during the day with an MCS.

3.2.1. Vehicle Specification

The initial stage of the process entails the calculation of the proportion of BETs among all incoming trucks at the designated site. A random selection of trucks is made, in accordance with the previously defined electrification rate, which are declared as BETs. In this manner, the simulation accounts for the random clustering of incoming BETs. The proportion of BETs at rest areas does not necessarily correspond to the general proportion of BETs for heavy long-distance trucks in stock. Rather, it depends on the availability of alternative charging options. For example, if there are no charging stations at neighbouring rest areas, a systematic accumulation of BETs at the location in question can be expected.

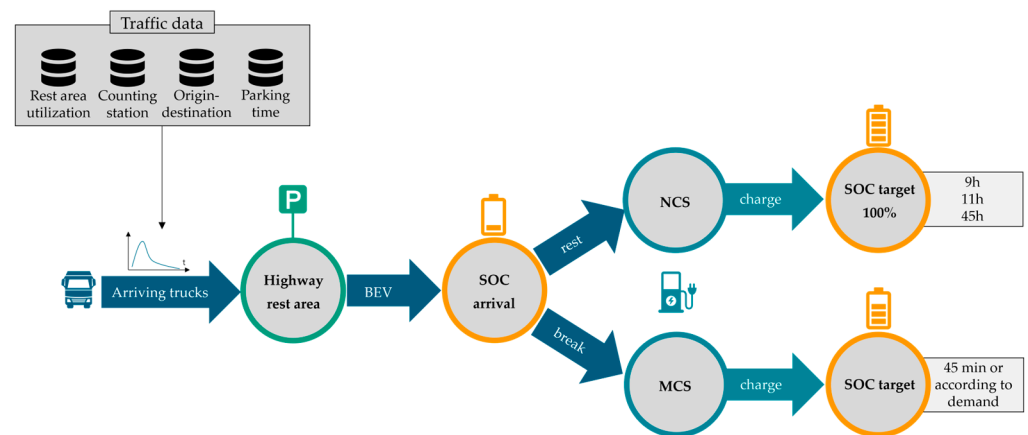


Figure 3. Overview of the simulation model.

A reason for the stop is then assigned to each BET. A distinction is made here as to whether the driver is taking a statutory break, a rest period or a weekly rest period at the rest area. The probability distributions defined in the mobility model for the course of the day on different weekdays are applied here. A length of stay of 45 min is stored for the breaks; for the rest period, 9 or 11 h is set, based on [35], at 50 percent each; for the weekly rest period, 45 h is set. The time periods are based on the statutory driving times for truck drivers in the EU [19,20]. If the planned stay ends at a time when lorries are prohibited from driving, the length of stay will be extended accordingly. The Sunday driving ban in Germany between midnight and 10 pm is taken into account here [50].

An average energy consumption of 1.2 kWh per km is assumed for the BET during the journey. Furthermore, it is possible to specify the usable size of the battery. In this context, three variants with a fixed battery size of 500, 650 or 800 kWh are considered for all vehicles, or a mix with 40, 40 and 20 percent of the sizes mentioned. In the case of the mix, the battery sizes are randomly assigned to the vehicles in accordance with the respective proportions. The underlying battery sizes are based on the future market expectations of the vehicle manufacturers [3]. A conservative assumption was made for the simulation.

The calculation of the charge levels and energy requirements is based on an average speed of 70 km/h and a maximum driving time of 4.5 h before the next mandatory break, in accordance with legislative requirements [19]. This results in a maximum driving distance of 315 km, which can also be driven with the smallest battery, with a reserve of 100 km considered.

The distributions for the distances defined in the mobility model are used to assign an individual remaining distance for each BET, which the vehicle still has to cover before the end of its trip. In the further course of the simulation, only the distances up to the next driving time break are relevant, which is why the remaining distances are limited to a maximum of 315 km for 4.5 h of driving, if necessary.

3.2.2. Charging Infrastructure Specification

This study considered two distinct charging systems for the truck charging park. The MCS was used for rapid intermediate charging of vehicles with high charging power, whereas the NCS was employed primarily for night charging with moderate power and extended parking times. On Saturdays, the NCS was also employed to charge the BETs during the day, when their drivers were at the rest area for the weekend. In the simulation, all BETs whose drivers arrived at the rest area for a break were assigned to the MCS. When the drivers arrived for a rest or weekly rest, the charging demands were processed via the NCS.

In the simulation, it was possible to specify the number of CPs for the MCS and the NCS separately. The maximum potential charging power was set at 1000 kW for the MCS and 100 kW for the NCS. A typical charging curve was defined for the MCS, based on the actual charging power requested by the BET. This results in a reduction in charging power

at a higher SOC, as illustrated in Figure 4. The charging power of the NCS was set at a constant level, irrespective of the SOC. The specified power values refer to the input side of the charging infrastructure. An efficiency factor of 0.9 was assumed for the overall system of charging infrastructure and vehicle for the charging process.

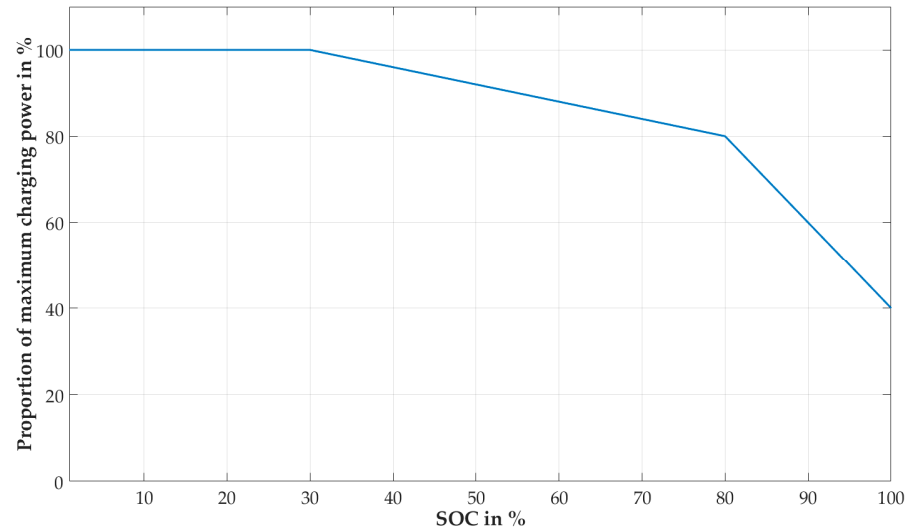


Figure 4. MCS charging curve.

If the number of available CPs is not sufficient to serve all vehicles immediately, waiting times will occur. As waiting times have a negative impact on logistic processes and cannot be counted towards the statutory break times, a limited willingness to wait is assumed depending on the SOC on arrival, as shown in Figure 5. If the waiting time is longer than the willingness to wait, the vehicle will not be charged at the truck CP.

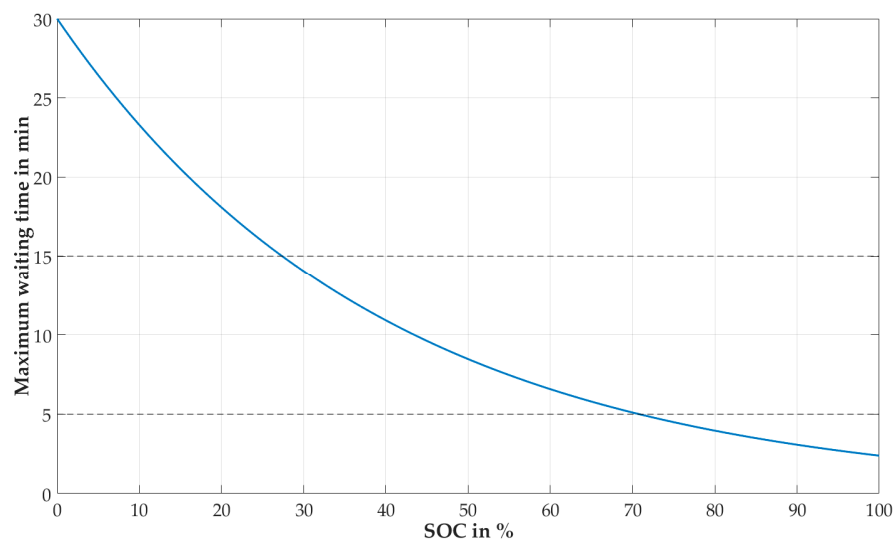


Figure 5. Willingness to wait before charging process.

3.2.3. Determining Charging Demand

In the context of this work, the SOC on arrival of the BET is generally assumed to be based on a full overnight charging. After an initial driving period of 4.5 h, a break of 45 min is to be taken during which opportune charging is possible at the MCS. A further driving period of up to 4.5 h is then possible until the subsequent overnight charge at the NCS, during which a rest period of at least 9 h must be observed. On Saturdays, the weekly rest period of 45 h begins in most cases after the first driving period with a recharge at the NCS.

The state of charge SOC_{start_1} at the start of MCS charging is calculated as follows, based on the first trip, considering the full usable battery capacity E_{batt} , the energy consumption E_{trip} for a driving period t_{trip} of 4.5 h at an average speed v of 70 km/h and a consumption E_{km} of 1.2 kWh/km:

$$SOC_{start_1} = \frac{E_{batt} - E_{trip}}{E_{batt}} * 100 \quad (10)$$

$$E_{trip} = t_{trip} * v * E_{km} \quad (11)$$

Considering the efficiency and the charging curve, the battery can be fully recharged in every scenario examined, provided that the BET is supplied with up to 1000 kW via the MCS during the 45 min break (**break charging**). Once the charging process is complete, the CP remains occupied until the end of the break. In this case, the SOC_{end_1a} at the end of the break is 100 percent. The SOC calculation for the evening NCS charging process and the Saturday weekly break is similar.

It should be noted that, particularly with larger batteries, the remaining SOC at the start of the MCS charging is still relatively high. This energy can therefore be used for the second driving period of the day. With MCS demand charging, instead of a full charge, only the missing energy needs to be charged in order to safely reach the destination or the site for the next driving time interruption (**on-demand charging**). In the simulation, an additional reserve for a range of 100 km is planned in any case. As the statutory break is usually not allowed to be interrupted, it has to be carried out separately after demand charging. The downtime at the CP thus corresponds to the actual charging time and is comparable to the refuelling of a conventionally fuelled truck.

In this case, the targeted state of charge SOC_{end_1b} at the end of the MCS charge can be calculated using the energy demand E_{trip_2} for the remaining distance s_{trip_2} and the reserve energy E_{backup} for the reserve range s_{backup} according to the following formula:

$$SOC_{end_1b} = \frac{E_{trip_2} + E_{backup}}{E_{batt}} * 100 \quad (12)$$

$$E_{trip_2} = s_{trip_2} * E_{km} \quad (13)$$

$$E_{backup} = s_{backup} * E_{km} \quad (14)$$

The target state of charge must be at least as high as the SOC_{start_1} on arrival and cannot exceed 100 percent. If the difference between SOC_{end_1b} and SOC_{start_1} is zero, the destination can be reached without demand charging and the BET is excluded from demand charging.

After the second driving period, the BETs have either already reached their destination or must stay the following night to charge at a rest area as well. For BETs whose drivers drive to the rest area to rest at the NCS, it is therefore assumed that two driving periods of 4.5 h each have been completed in advance. If only an MCS demand charge is carried out after the first driving period, the energy required for a full charge in the evening is accordingly higher. The SOC_{start_2} in percent at the start of the NCS is calculated as follows:

$$SOC_{start_2} = SOC_{end_1b} - \frac{E_{trip}}{E_{batt}} * 100 \quad (15)$$

The CPs of NCS are occupied for the entire duration of the rest or weekly rest. The charging power of 100 kW was selected to ensure that the batteries are fully charged within the legal standing time of at least nine hours in each scenario.

3.2.4. Simulated Charging Process

The modelling of the charging infrastructure for the MCS and NCS was carried out using the MATLAB/SIMULINK R2015b program as part of a load flow simulation for local energy systems. The work was based on the simulation of DC charging stations for

urban fast-charging parks for passenger cars [51]. The time step size of the simulation was one minute in order to adequately resolve the frequently brief charging durations and the associated load peaks. Each simulation was performed over a one-year period. The functions of the charging infrastructure model that were pertinent to this study are described below.

The number of BETs arriving per minute t and having a charging demand are each assigned to a free CP and charged in each time step with the maximum possible charging power $P_{charge}(SOC)$. The maximum charging station power P_{CP} , the charging curve of the BET $\varepsilon_{truck}(SOC)$ and the efficiency ρ are taken into account.

$$P_{charge}(SOC) = P_{CP} * \varepsilon_{truck}(SOC) * \rho \quad (16)$$

At the end of each minute t , the $SOC(t)$ of all charging BETs is adjusted with the amount of energy $E_{charge}(t)$ charged in the time step Δt .

$$SOC(t+1) = SOC(t) + \frac{E_{charge}(t)}{E_{batt}} * 100 \quad (17)$$

$$E_{charge}(t) = P_{charge}(SOC(t)) * \Delta t \quad (18)$$

The BETs are either charged to a predefined target SOC (on-demand charging) or for a predefined standing time at the CP (break charging, NCS charging). In the first case, the CP is left after charging is complete; in the second case, the CP is blocked until the parking time has elapsed. However, a minimum charging time of five minutes is set in any case for a charging process that has been carried out. When vehicles are replaced at a CP, two min are set aside for this, during which no charging can take place.

If all CPs are already occupied, subsequent BETs are placed on a waiting list and can occupy a CP that becomes available later. If the waiting time exceeds the driver's willingness to wait, the BET will not be charged.

The charging processes at the MCS and NCS are simulated in parallel within distinct programme sections, allowing for the independent assessment of results and an integrated analysis of the entire charging park.

3.3. Reference Site and Scenarios

To illustrate the capabilities of the presented simulation tool, a series of scenarios for a reference site are analysed. The reference site is defined in analogy to the Lipperland-Süd rest area on the A2 highway in Germany. In the case of the reference site, it is assumed that there are 93 regular truck parking spaces available for one direction of travel. To quantify the volume of truck traffic at the rest area, the hourly vehicle counts for semitrailer trucks at the nearest highway counting station, Brönninghausen [52], in the direction of Hannover, from 2022, are also employed. A total of 2,144,075 trucks were registered in the whole of 2022 as part of the counts. The methodology presented in Section 3.1 was employed to derive the number of trucks arriving at the site during the period for break-times, rest, or weekly rest. In all scenarios, the share of BETs among the arriving vehicles was set at 20 percent, unless otherwise stated in the evaluation.

As part of the analysis, further specific parameters for the vehicles and the charging infrastructure are defined individually in the scenarios, in addition to the general boundary conditions already described. A differentiation is only made for intermediate charging at the MCS. Overnight or weekend charging at the NCS is conducted in all scenarios with a charging capacity of 100 kW for the entirety of the truck's presence, which is 9, 11, or 45 h, respectively. The simulated scenarios can thus be defined as follows:

- *Scenario 1—Break charging*

Following a 4.5 h driving period, the vehicles are received for intermediate charging and are fully charged at the MCS CPs, which have a maximum charging power of

1000 kW for the entire 45 min break. All BETs are specified to have a usable battery size of 500 kWh. A total of 11 CPs are set aside for the MCS, and 36 for the NCS.

- *Scenario 1a—Break charging with a limited number of charging points*
In comparison to the preceding scenario, the number of MCS CPs is reduced from eleven to seven.
- *Scenario 2—On-demand charging*
Following a period of 4.5 h of driving, the BETs are charged at the MCS CPs, which have a capacity of up to 1000 kW. The charging process is concluded when the vehicles are able to complete the remaining distance (including a reserve of 100 km) with the achieved charge level (see Sections 3.2.1 and 3.2.3). The usable battery size is set in three different variants for all BET models, at 500, 650 or 800 kWh. In addition, a mixed variant with mixed battery sizes of 40, 40 and 20 percent of the sizes mentioned is evaluated. A total of 11 CPs are designated for the MCS, while 36 CPs are allocated for the NCS.
- *Scenario 2a—On-demand charging with a limited number of charging points*
In comparison to the preceding scenario, the number of MCS CPs is reduced from eleven to four. The evaluation of this scenario is conducted with regard to the battery sizes for the so-called mixed variant.
- *Scenario 3—Combination of break charging and on-demand charging with a limited number of charging points*
The third scenario is a combination of the preceding two scenarios. In this scenario, batteries with longer charging times are charged during their 45 min break, a process analogous to that described in Scenario 1. In contrast, vehicles with lower charging demands and thus shorter charging times are only charged as required, which corresponds to an approach similar to Scenario 2. Within the set mixed variant, differentiation is made based on battery size. BETs with a 500 kWh battery charge during the break, while all other BETs charge as required. The number of MCS CPs is limited to five, while 36 CPs are again set aside for the NCS.

4. Results

The following section presents and discusses the results of the simulation-based evaluation of the various scenarios for the defined reference site. Initially, the results from the mobility model regarding the volume of truck traffic at the rest area are presented (4.1). This is followed by an evaluation of the individual scenarios (4.2–4.4) and a comparative summary of the main results of the scenarios (4.5).

4.1. Truck Parking and Mobility Behaviour at the Rest Area

The truck attendance times derived from the mobility model at the rest area in question, which has 93 regular parking spaces, show regular overcrowding at night and at weekends. Figure 6 shows the average predicted truck park utilisation as a function of road capacity utilisation.

The resulting distribution of trucks present at the same time as shown in Figure 7a provides information about the frequency of the overloading situation at rest stops. At peak times, 150 vehicles are registered on site, 57 more than the number of regular parking spaces available (see Figure 7a). Consequently, with an electrification share of 20 percent of the vehicles at the site (as assumed in the simulation), more than 20 percent of the regular parking spaces must be equipped with CPs to meet demand without service restrictions, as shown in Figure 7b for the temporal distribution of the BETs present at the same time. At peak times, 36 BETs take up 39 percent of the 93 regular parking spaces. In this regard, it should be mentioned that overcrowding and random accumulations of BETs at the location play a decisive role in the case of low electrification shares. With an increase in the number of CPs, conventionally powered trucks are displaced to non-regular parking spaces (e.g., in the lanes, in the second row or in areas for passenger cars). The rest area is used by

12,023 BETs throughout the year, with 5919 taking a break time, 5203 resting and 901 taking a weekly rest time.

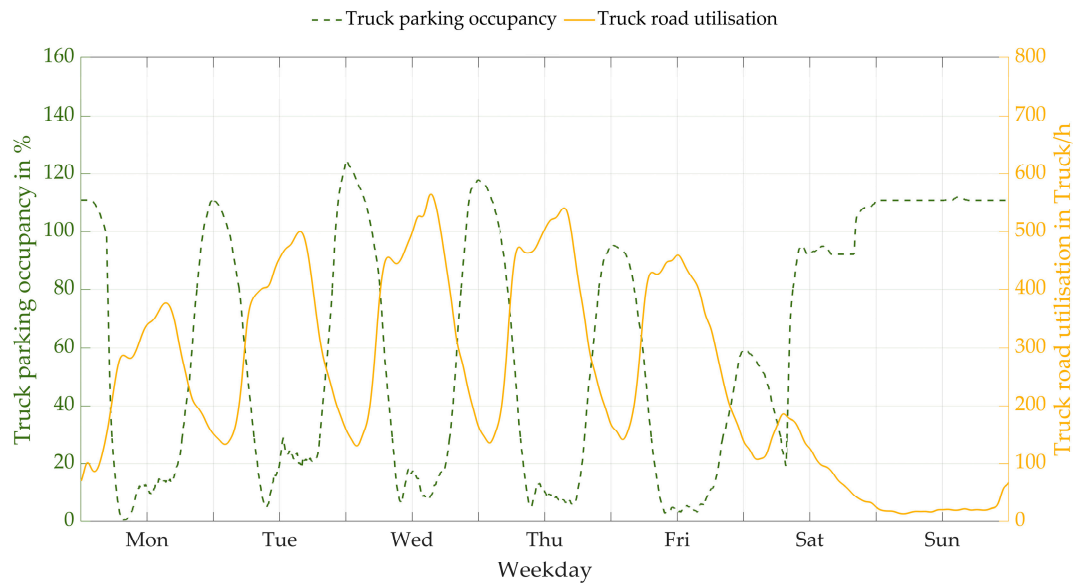


Figure 6. Average truck park occupancy and road utilisation at the rest area.

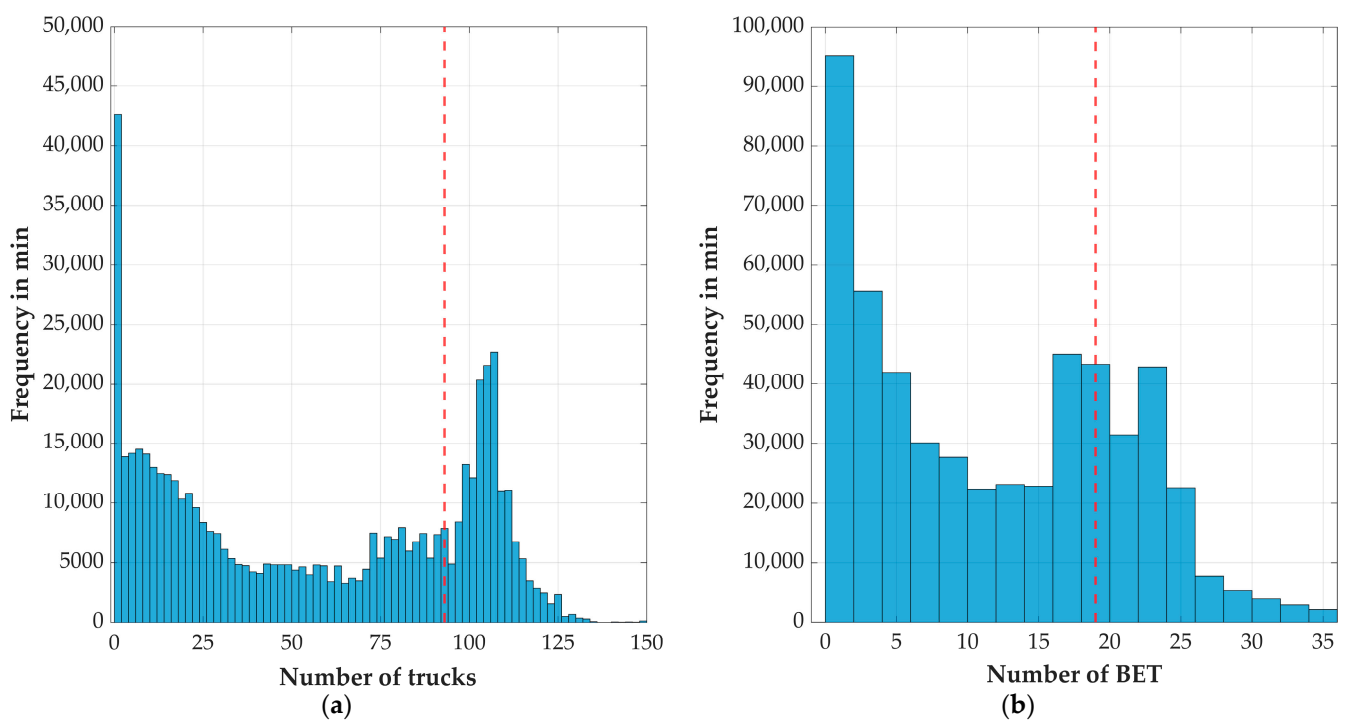


Figure 7. Distribution of trucks present at the same time: (a) truck utilisation of the rest area (maximum: 150 trucks, red line: 93 regular parking spaces at the rest area); (b) BET utilisation of the rest area with an electrification share of 20 percent (maximum: 36 BETs, red line: 20 percent of the regular parking spaces).

For scenarios 2, 2a and 3, the remaining driving distances for the trucks at the rest area under consideration are taken into account for charging. In accordance with the methodology presented for the mobility model (see Section 3.1.2), the potential driving routes of the trucks were modelled and randomly assigned according to the distribution in Figure 8.

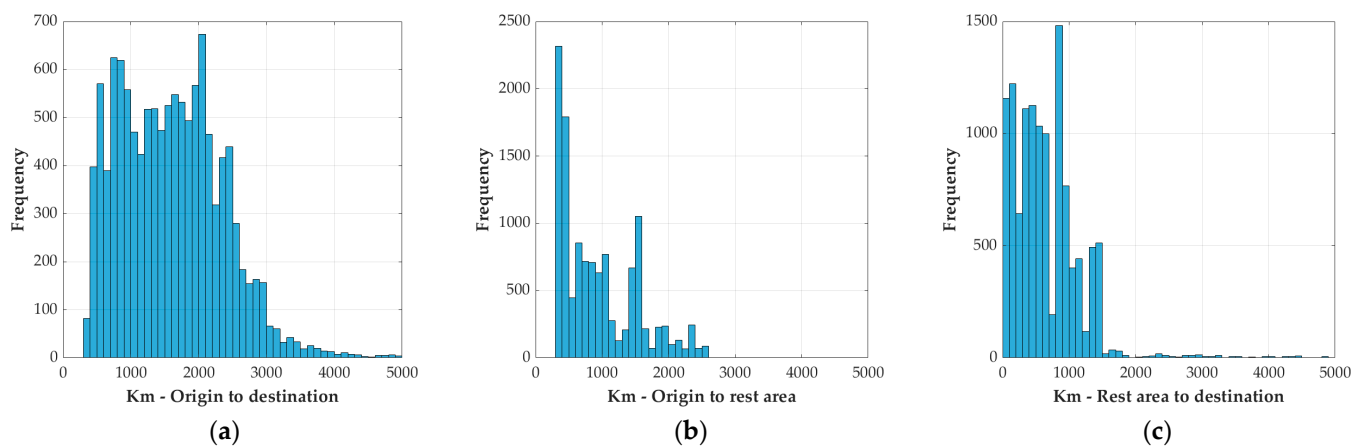


Figure 8. Potential trip distances for the trucks at the rest area. Distances from (a) origin to destination, (b) origin to rest area, (c) rest area to destination.

4.2. Scenario 1—Break Charging

At least 11 MCS CPs and 36 NCS CPs are required for a full supply without waiting times. Up to 10 vehicles charge simultaneously at the MCS CPs and a maximum of 30 vehicles at the NCS CPs. The higher demand for CPs results from the additional parking times after the end of charging until the respective break and rest periods are completed. The pure charging time is 32 min for MCS charging and 253 min for NCS charging. The average utilisation of the charging infrastructure over the course of the week can be seen in Figure 9.

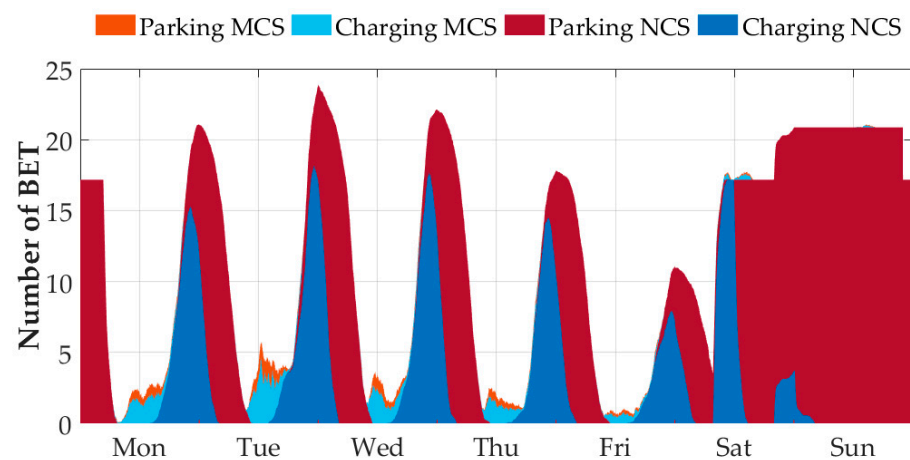


Figure 9. Average utilisation of the charging infrastructure over the course of the week in scenario 1.

The demand for MCS interim charging is particularly low at night and at weekends. The corresponding parking spaces could therefore be released for night charging or weekly rest at these times. For MCS, each CP is used for 538 charging events per year on average. They are blocked for 4.6 percent of the time of the year on average, with a minimum of 0.1 and a maximum of 16.9 percent for a single CP. For NCS, each CP is used for 170 charging events per year on average (min 1, max 308). The CPs are blocked for 30.2 percent of the time of the year on average (min 0.1, max 55.6 percent). Charging occurs in 8.2 percent of the time, with the assumed charging power of 100 kW per CP.

With a shared grid connection for the charging infrastructure, the peak load is 8808 kW. The peak load is largely determined by MCS charging (see Figure 10).

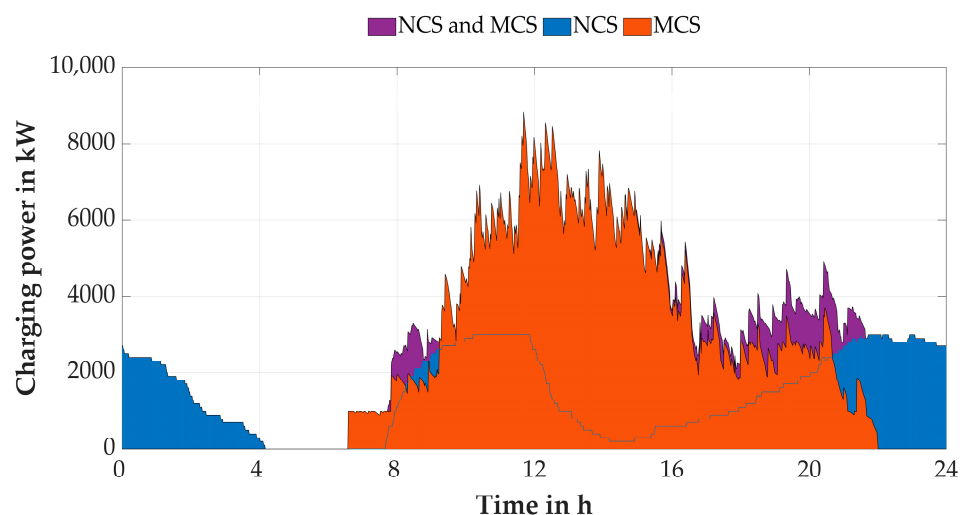


Figure 10. Peak load analysis for the charging park in Scenario 1.

Figure 10 shows the annual peak loads for each minute of the day. The peak loads for MCS mainly occur on weekdays during the day, while the peak loads for NCS occur on weekdays in the late evening and on Saturday mornings. The peak loads of the total charging park are usually lower than the sum of the peak loads of MCS (8808 kW) and NCS (3000 kW), as the individual peak loads occur at different times. The total energy supplied at the charging park is around 5049 MWh for the simulated year. About half of this is accounted for by MCS and NCS, respectively.

In view of the long idle times, a charging capacity of 50 kW per CP would be sufficient for NCS charging to cover the demand in Scenario 1. However, this would be irrelevant for the peak load of the entire charging infrastructure.

The battery size has no influence on the results in Scenario 1, as the energy consumed during the previous driving time of 4.5 h is fully recharged over the entire and sufficient standing time in each case.

Scenario 1a—Break charging with a limited number of charging points

In Scenario 1, there are only a few occasions when more than seven MCS CPs are occupied at the same time (33 h p.a.). From a technical and economic perspective, a corresponding restriction of MCS CPs therefore appears to make sense, which can be implemented with only minor restrictions at the rest area. As a result of the limitation to seven CPs, there are waiting times before charging at 418 BETs. This corresponds to 7.1 percent of BETs with MCS charging requirements. The waiting times of the affected vehicles vary between 1 and 15 min (median: 5 min). Up to six vehicles are waiting at the same time, and 66 BETs cannot be served due to longer waiting times, which corresponds to a share of 1.1 percent. The implemented measure leads to a reduction in the peak load of the entire charging infrastructure by 25 percent to 6567 kW. For MCS, the average number of annual charging events per CP increases to 836, and the time utilisation increases to 7.2 percent.

Under the assumptions of Scenario 1 (break charging), an increase in the proportion of electrified vehicles by 5 percent points would require an increase in the number of MCS CPs by around 1.3 to maintain a comparable service quality (see Figure 11).

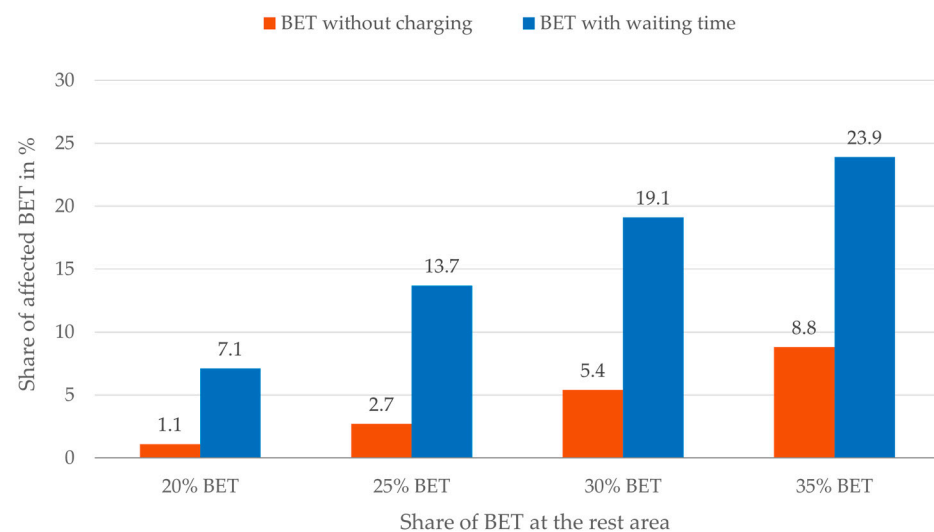


Figure 11. Development of service quality at the rest area with increasing electrification of vehicles and 7 MCS CP in Scenario 1a.

4.3. Scenario 2—On-Demand Charging

With MCS charging in Scenario 2, it must be considered that only the energy requirement up to the next potential charging stop (including 100 km reserve) is covered. As a result, the battery size of the vehicles plays a key role in charging infrastructure planning. While all vehicles with a 500 kWh battery must be charged, the charging requirements for larger batteries are reduced by up to 25 percent. Some vehicles can reach their daily destination without intermediate charging with the available remaining charge level after the first driving time (including reserve). However, most vehicles still have a full driving time of 4.5 h (315 km, 378 kWh + 120 kWh reserve) to complete before reaching their next interim destination, which requires an interim charge in any case. With an 800 kWh battery, however, this is only necessary to guarantee the 100 km reserve. Vehicles with batteries over 876 kWh would no longer require any intermediate charging.

When charging on demand, only significantly shorter charging times are required for the larger batteries, in the range of five to eighteen minutes, but these are in addition to the pause time. The requirements regarding the number of CPs and the grid connection are also reduced. In the mixed variant with mixed battery sizes, only eight MCS CPs are required to cover all demand without waiting times. This reduces the peak load by 18 percent compared to Scenario 1. A summary of all the key results of the analysis can be found in Table 1. In the mixed variant, the battery sizes were set at 40 percent with 500 kWh, 40 percent with 650 kWh and 20 percent with 800 kWh.

Table 1. Demand charging without service restrictions for different battery sizes in scenario 2.

Battery Size	500 kWh	650 kWh	800 kWh	40/40/20% Mix
Charges MCS	5919	5170 (−13%)	4467 (−25%)	5341 (−10%)
Charge duration for MCS	≤32 min	≤18 min	5–6 min	5–32 min
Occupied MCS CP (charging)	10 (10)	8 (8)	5 (5)	8 (8)
Peak load charging park	8808 kW	7206 kW	4464 kW	7247 kW

The utilisation in the mixed variant is 668 charging events per MCS CP per year on average (min 6, max 2806). The time utilisation is 2.4 percent. For NCS, the only change in CP utilisation compared to Scenario 1 is the longer charging times due to the larger batteries, which were only partially charged during the intermediate charge. The average time utilisation for charging is 10.4 percent. Compared to Scenario 1, the energy demand has partly shifted from MCS to NCS: 70 percent of the energy demand now occurs during

NCS charging. The total energy requirement is slightly lower at 4665 MWh, as some vehicles with larger batteries and shorter remaining driving distances no longer require MCS charging.

Scenario 2a—On-demand charging with a limited number of charging points

Reducing the eight MCS CPs required for the mixed variant in Scenario 2 to four MCS CPs results in waiting times before charging for 214 BETs. This corresponds to 4.0 percent of the BETs with MCS charging requirements. The waiting times of the affected vehicles vary between 1 and 14 min (median: 5 min). Up to four vehicles are waiting at the same time. As a result of the waiting times, 60 BETs cannot be served, which corresponds to 1.1 percent. The reduction of 8 MCS CPs required for the mixed variant in Scenario 2 to 4 MCS CPs leads to a reduction in the peak load of the entire charging infrastructure by 34.9 percent to 4715 kW. For MCS, the average number of annual charging events per CP increases to 1320 (min 339, max 2829), and the time utilisation increases to 4.8 percent.

Compared to Scenario 1a, the number of MCS CPs is 43 percent lower (4 instead of 7 CP), with a comparable service quality. The peak load is 28.2 percent lower than the value of 6567 kW in Scenario 1a. In terms of the requirements for the charging infrastructure and the grid connection, Scenario 2a is therefore the most efficient setting.

4.4. Scenario 3—Combination of Break Charging and on-Demand Charging with a Limited Number of Charging Points

As explained in the previous scenarios, MCS demand charging with larger batteries only results in relatively short charging times. The CPs are not occupied over a fixed pause period of 45 min, which ensures more efficient utilisation of the infrastructure. However, if the smaller 500 kWh battery is used, the charging time is extended to up to 32 min, which is in addition to the actual pause time and can significantly impair the logistics process. In Scenario 3, the vehicles with the 500 kWh batteries are therefore excluded from on-demand charging and charged during the break in the same way as in Scenario 1. A limitation to five MCS CPs ensures a comparable service quality as in Scenarios 1a and 2a. Here, 222 BETs (4.2 percent) are affected by waiting times of between 1 and 15 minutes (median: 5 minutes), with up to five vehicles waiting at the same time, and 60 vehicles (1.1 percent) cannot be charged due to longer waiting times. The utilisation is 1056 charging events per MCS CP per year on average (min 234, max 2424). The time utilisation is 5.5 percent.

In Scenario 3, a peak load of 4960 kW is forecasted for the entire charging infrastructure, which corresponds to a decrease of 24 percent compared to Scenario 1a. The peak load is still largely characterised by MCS charging (see Figure 12).

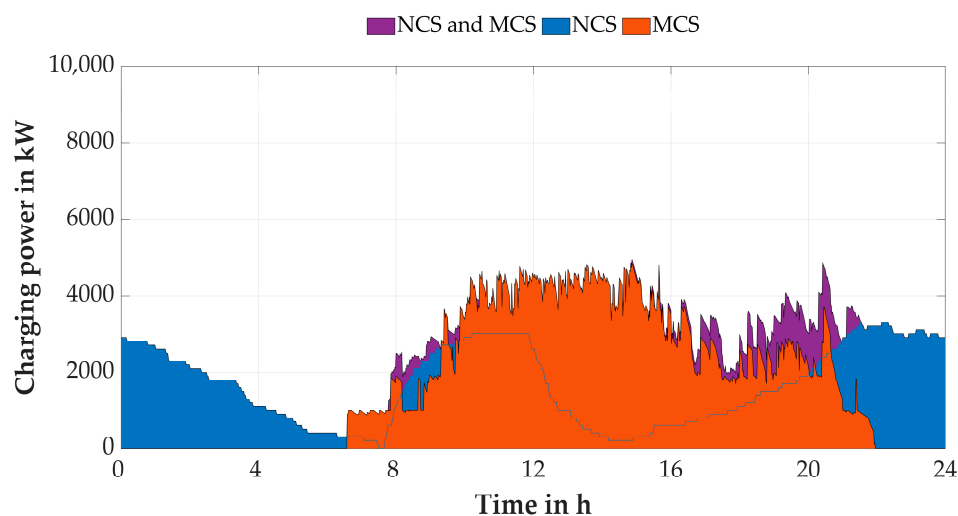


Figure 12. Peak load analysis of the charging park in scenario 3.

Figure 12 shows the annual peak loads for each minute of the day. As in Scenario 1, the peak loads for MCS mainly occur on working days during the day, while the peak loads for NCS occur on working days in the late evening and on Saturday mornings. The total energy supplied at the charging park is around 4800 MWh for the simulated year.

To guarantee the quality of service even with increasing shares of electrification, under the boundary conditions of Scenario 3, only an expansion of less than one MCS CP per five percent points higher share of electrification is required (cf. 1.3 CP in Scenario 1a). With a share of 50 percent purely electric trucks at the location, for example, 10 MCS CPs are required. As a result, 6.3 percent of BETs would be affected by moderate waiting times, while 1.1 percent of BETs would remain without charging. In this case, the peak load of 9187 kW would be around 85 percent higher than the previous value in Scenario 3 (20 percent BET), with an increase in the proportion of electrification, and consequently also the charging requirements and charges, of around 150 percent.

4.5. Comparative Summary of the Main Results of the Simulated Scenarios

Table 2 summarises the main results of the described scenarios. The differences mainly concern the MCS part. For NCS, the energy demand in Scenarios 2 and 3 is higher than in Scenario 1 due to the larger truck batteries, which were only partially charged during the intermediate charge. Therefore, the average charging times are also longer. In any case, the demand can be met with the set charging power of 100 kW per NCS charging point.

Table 2. Main results of the simulated scenarios for MCS charging.

Scenario—MCS	S1	S1a	S2 (mix)	S2a	S3
Charges MCS	5919	5853	5341	5281	5281
With waiting time	-	418	-	214	222
BET without service	-	66	-	60	60
MCS CP	11	7	8	4	5
Avg. charges p. CP	5919	5853	5341	5281	5281
Min.	15	206	6	339	234
Max.	1976	1986	2806	2829	2424
Avg. time utilisation p. a.	4.6%	7.2%	2.4%	4.8%	5.5%
Charging only	3.3%	5.1%	2.4%	4.8%	4.4%
Peak load charging park	8.8 MW	6.6 MW	7.2 MW	4.7 MW	5.0 MW
Peak load MCS only	8.8 MW	6.6 MW	7.2 MW	4.0 MW	4.9 MW
Peak load NCS only	3.0 MW	3.0 MW	3.3 MW	3.3 MW	3.3 MW
Charged energy p. a.	5049 MWh	5022 MWh	4665 MWh	4655 MWh	4800 MWh
Share of MCS	49%	49%	30%	30%	32%
Share of NCS	51%	51%	70%	70%	68%

5. Discussion

The simulation developed in this study was used to evaluate potential designs of a charging infrastructure for BETs at a highway rest area. As part of the study, MCS break charging was analysed for an electrification share of 20 percent of the trucks arriving at the site. With eleven MCS CPs, it is possible to fully cover all MCS charging requirements without waiting times. This scenario shows that many CPs are insufficiently utilised. This leads to an economically unattractive organisation of the construction and operation of the cost-intensive infrastructure. Simultaneously, there are high, but rarely occurring load peaks. The latter generally require high-performance grid connections and an associated expansion of the higher-level energy infrastructure, which is associated with high costs and long planning and implementation times for the operator. If the number of CPs is reduced and/or the proportion of electrified trucks increases, there will be waiting times at the charging park, and it will no longer be possible to adequately meet all charging requirements.

However, the analysis carried out shows that the service restrictions mentioned only occur to a minor extent if the number of CPs is reduced to a moderate extent. Simultaneously, the measure results in a significant improvement in the peak load. Furthermore,

the organisation of the waiting vehicles on site must be considered. Without additional information before charging, it is not possible to estimate the expected waiting time and the availability of a free CP. In the worst-case scenario, this process may take up to 45 min for break charging. A reservation system can provide more transparency here, but waiting times must also be considered when using it, as a buffer should be planned for the arrival times in order not to miss the reserved time slot. These buffer times would consequently affect all BETs. Such a system also has limited resilience regarding delays or charging infrastructure failures. At times of high-capacity utilisation, there are no alternative charging options available for the drivers concerned. Adequate spaces must be provided on site for waiting vehicles to avoid obstructing other vehicles. To avoid losing regular parking spaces, the waiting area could be in the petrol station area of the service station in conjunction with a guidance system.

In Scenario 2, MCS demand charging was considered, in which the CP is only used for charging and only the energy required for the remaining distance travelled (incl. reserve) is recharged. Accordingly, larger batteries have a significantly lower charging requirement with correspondingly shorter charging times. Compared to break charging, the number of CPs required is lower, while utilisation is higher and peak loads are significantly lower. An increase in battery capacity is expected in the future [3], and research is already being carried out into systems with several MW of charging power [27], which could lead to a further reduction in charging times. Under these boundary conditions, charging the BET is no more time-consuming than refuelling a conventionally powered truck. For vehicles with smaller batteries, however, which arrive with a low charge level after the first driving time, on-demand charging proves to be disadvantageous. In this case, the charging time of more than half an hour would have to be completed in addition to the statutory break. To counteract this, a mixed system with on-demand and break charging was proposed in Scenario 3. Alternatively, it is possible to divide the prescribed break time of 45 min into two parts of 15 and 30 min, respectively. The extent to which these individual time slots could be used for charging needs to be examined. However, the separation of charging and break times also offers an advantage: depending on the battery capacity and charge level, intermediate charging can be postponed compared to the break. This means that utilisation peaks in the infrastructure can be avoided. By applying dynamic pricing over time, charging infrastructure operators can further increase capacity utilisation and additionally reduce peak loads. Another option for optimising the charging infrastructure is to relocate the infrastructure to a drive-through area, similar to petrol stations. This allows the already scarce parking spaces to be used by a larger number of vehicles. In addition, competition between BETs and diesel trucks for parking spaces can be avoided. Flexible use of the car parks for rest periods and breaks also remains guaranteed.

In Scenario 3, a combined system with break and on-demand charging options was analysed to combine the advantages of both variants. The spaces for break charging could be offered via a reservation system. In the event of a disruption or delay, drivers can switch to the on-demand CPs. Although this would lead to longer standing times and possibly additional waiting times, at least every vehicle could still be charged even if reservations were cancelled. For a combined scenario, suitable business models need to be developed that offer incentives for infrastructure-friendly charging behaviour. In addition to the dynamic pricing already mentioned, an energy rated tariff for on-demand charging could be supplemented by a surcharge for longer charging times.

For the analyses carried out, it was assumed that the vehicle batteries were fully charged overnight. The integration of charging infrastructure in depots or at other truck parking spaces is proving to be challenging; therefore, it cannot be assumed that every vehicle will have overnight charging facilities. It is not yet possible to estimate how the problems described will affect user behaviour. The question arises as to how BETs can be operated without restrictions. It also needs to be determined whether additional on-demand charging will be carried out at a public charging infrastructure before or after the tour. Another possibility would be that vehicles with large batteries are prioritised and

charged to the maximum when the opportunity arises. This could lead to higher charging requirements for MCS intermediate charging and public night charging than assumed in the simulation. On-demand MCS intermediate charging, on the other hand, places greater demands on the overnight charging options, as vehicles with larger batteries also end their daytime journeys with low charge levels. In conjunction with MCS break charging, a charging capacity of less than 50 kW per CP is sufficient for night charging. In the case of intermediate charging only as required, a higher charging capacity must be calculated for large batteries and short rest periods. The future standard used for night charging has also not yet been determined. An alternating current interface appears suitable for outputs up to 44 kW; for higher outputs, charging can be carried out with a direct current via a CCS interface. The MCS standard could also be suitable for charging at lower power levels. The implementation of any of these options is largely dependent on the range offered by the vehicle manufacturer.

If both systems are installed independently at the site, it must be ensured that the maximum possible grid consumption can also be guaranteed independently. As MCS charging mainly takes place at midday on weekdays, but NCS charging only ramps up in the late afternoon or on Saturdays, the peak load for the overall system is significantly lower than the total for the two individual applications. It is therefore necessary to organise the infrastructure at the site holistically and secure it via a joint energy management system. Ideally, the charging infrastructure for cars at the highway sites should also be integrated.

6. Summary and Outlook

As part of this work, a simulation-based tool was developed to support the strategic and technical planning of truck charging parks at highway locations. The method and the underlying mobility model can be applied to any highway rest area in Germany. The analysis options were demonstrated using a reference site and the results were presented and discussed. Using a scenario-based approach, uncertain parameters can now be varied, and a wide variety of charging park designs can be analysed and compared.

The reference analysis with the new simulation tool has shown that larger batteries expected in future BETs can have a significant impact on the requirements of truck charging parks. They allow a switch in the MCS charging strategy from break charging during the statutory 45-minute driving breaks to an ad hoc demand charging, to arrive safely at the destination. The result is a much lower demand for MCS charging points and more efficient use of them. This can significantly reduce the peak load at the site. The analysis was able to determine the charging infrastructure requirements for MCS and NCS, peak loads, energy conversion rates and infrastructure utilisation based on the modelled traffic at the site.

In addition to the technical and organisational aspects, further work should also consider the economic effects of the different design options for the charging parks. Furthermore, additional functionalities can be added to the simulation and further scenarios can be added to the analysis: The effects of higher MCS charging capacities, no or only partial night charging, local power generation and the use of load management and stationary battery storage systems should be analysed. Corresponding analyses are planned as part of the HoLa project [26]. Furthermore, the input database for the simulations needs to be optimised to obtain more precise mobility data for incoming trucks at specific locations. In this respect, automated measurements at the locations should replace the data from the mobility model in the future.

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