RE-xpertise

ef RUHR
DIE ENERGIEDENKFABRIK

GRID-RELATED CHALLENGES OF HIGH-POWER AND MEGAWATT CHARGING STATIONS FOR BATTERY-ELECTRIC LONG-HAUL TRUCKS

on behalf of
Transport and Environment
Square de Meeûs, 18, 2nd floor
B-1050 | Brussels | Belgium

Authors

Dr.-Ing. Karsten Burges

RE-xpertise
Bölschestr. 30
D-12587 Berlin

Dr.-Ing. Stefan Kippelt

ef.Ruhr GmbH
Emil-Figge-Str. 76
D-44227 Dortmund

Further information

T&E | Fedor Unterlohner | fedor@transportenvironment.org

RE-xpertise | Dr.-Ing. Karsten Burges | info@RE-xpertise.de

ef.Ruhr | Dr.-Ing. Marco Greve | marco.greve@efruhr.de

To cite this study

K. Burges, S. Kippelt, “Grid-related challenges of high-power and megawatt charging stations for battery-electric long-haul trucks”, study on behalf of Transport & Environment, 2021

Acknowledgement

This study was commissioned and supported by Transport & Environment.

Summary

Motivation, objectives and scope

Battery-electric long-haul (BE-LH) trucks are one of the technology options for decarbonising the road freight sector. A precondition for battery-electric traction is the availability of a sound and reliable charging infrastructure.

The objective of the study is to identify and to contribute to a better understanding of potential grid-related challenges of high-power and megawatt charging stations for BE-LH trucks. This study evaluates charging configurations, the implications for grid connections, related investments for the assets and examines potential barriers.

The charging infrastructure demand of BE-LH trucks will be diverse, depending on the individual requirements of haulage companies, like typical freight movements, trip distances, loading and unloading times and driving shifts. Charging opportunities can be generally broken down to:

- Public high-power (HPC) and megawatt charging (MCS),
- (Semi-)public HPC and overnight charging (NCS) at the place of (un)loading of freight,
- Public NCS during longer rest periods, and
- Private NCS at the depot when the truck returns from single- or multiday travel.

Because of the high connection power of the MCS, we presume a local distribution grid at medium-voltage (MV) level. MCS are connected to the MV-level with a distinct MV/LV transformer (1.5 MVA). The same type of transformer is used to connect 8 NCS to the local MV grid or 3 HPC, using a small LV grid (see Figure 2-6).

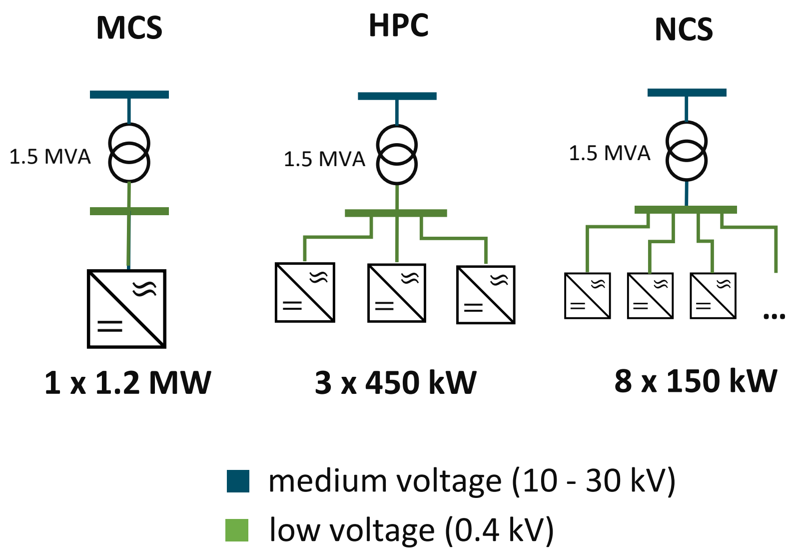


Figure 1: Grid connection of chargers

In this study, we focused on public and semi-public charging and analysed three prototypes of charging infrastructure, covering and illustrating the range of requirements:

1. **Highly frequented public charging station (MCS and NCS, prototype 1)**: a public charging station along the motorway network with intense long-haul traffic, representing the upper bound of public charging demands;
2. **Remote, less frequented public charging station (MCS and NCS, prototype 2)**: a public charging station along the motorway network with minor long-haul traffic, representing the lower bound of public charging demands;
3. **Commercial logistics hub (HPC and NCS, prototype 3)**: a medium-sized logistics hub with multiple haulage companies combining long- and short-haul trucks.

Key findings at a glance

The three prototypical charging stations cover a large share of the charging infrastructure required for the future transition to BE-LH trucks. They are technically feasible and the offered service levels match with the current operational processes of logistics companies.

Active charging management is a crucial factor for the reduction of grid connection costs and can be integrated without affecting the service level of the charging stations.

All prototypes require a grid connection at medium or high voltage level.

Space requirements at motorway stations will slightly increase.

In case of logistics hubs (prototype 3), the structure of the area and operational processes will need to be adapted. Dedicated and accessible space for public charging at those hubs, also overnight, will be an essential part of the concept.

The required capacity of the network connection for the charging infrastructure at logistic hubs is in a range between 0.5 MW/hectare and 1 MW/hectare. This is a factor 10 to 20 compared to the current situation. Strong HV-distribution networks in the vicinity of logistics hubs may become an important factor for site development.

With all prototypes, the specific costs of the charging infrastructure are dominated by the cost of the chargers – in most scenarios they represent about 90% of total infrastructure costs. The cost per kWh related to the grid connection is, in most cases, not more or below 10% of the total infrastructure-related costs. Hence, the charging infrastructure can grow incrementally, without significant additional costs. The level required for refinancing the infrastructure of the prototypes considered is about 0.05 €/kWh to 0.06 €/kWh charged, corresponding to about 7 € per 100 km driving[1]. Only in the case of public charging stations with low traffic volume (prototype 2), the specific monetary value of the infrastructure is higher (0.10 €/kWh to 0.14 €/kWh). These numbers neither include costs for electricity supply, taxes, levies, charges or profit margins nor costs for planning, permitting or extra space at the site.

[1] For the BE-LH trucks, we assume a specific energy consumption of 1.26 kWh/km ‘plug to wheel’.

Scenario framework, configurations and results

Public charging stations (prototypes 1 and 2)

The study considers different penetration rates of BE-LH trucks in the total LH truck fleet. These levels may be associated with the years 2027, 2030 and 2040. For the two prototypes of **public charging stations,** Figure 2 indicates major parameters per scenario snapshot, such as the average distance between charging stations and the penetration rate of BE-LH trucks in the truck fleet passing along this station.

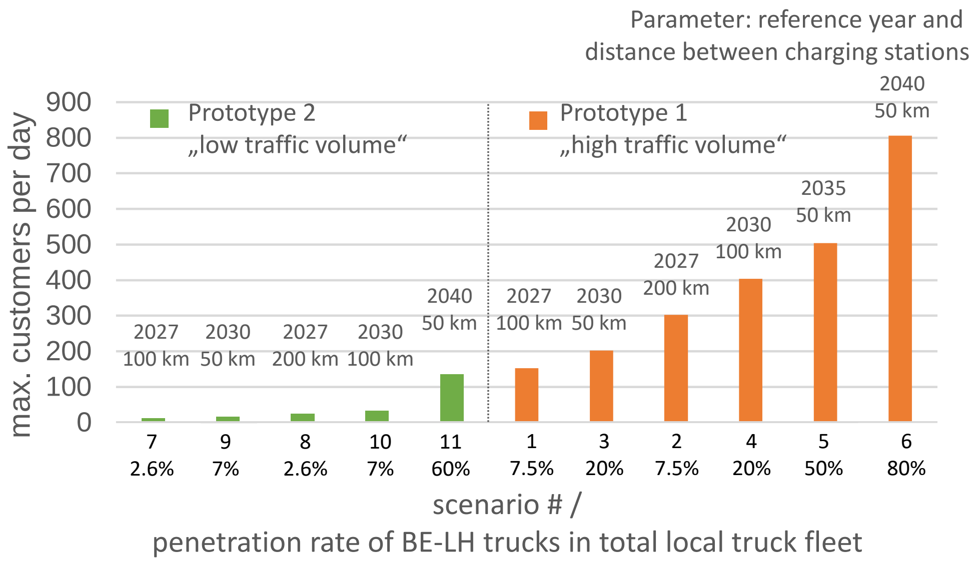


Figure 2: **Maximum daily MCS customer volume and underlying assumptions for the various scenario snapshots**

We assume the design of a public charging station to be similar to nowadays motorway service areas. MCS are offered at special stands that can be used for the duration of the charging process only. Overnight parking and charging are available at separate bays. Standing times for overnight charging are determined by the mandatory rest period and not by the duration of the charging process.

There are synergy effects between NCS and MCS and it is highly recommended to combine these charger types at one charging station.

The simulations show that, as a rule of thumb, one MCS charger per 50 to 60 customers per day has to be installed. The MCS chargers require a grid connection capacity at the level of the installed capacity. If more than 100 MCS customers per day have to be served, with the given assumptions, the number of NCS chargers grows proportional with the number of MCS chargers (ratio about 15 to 1).

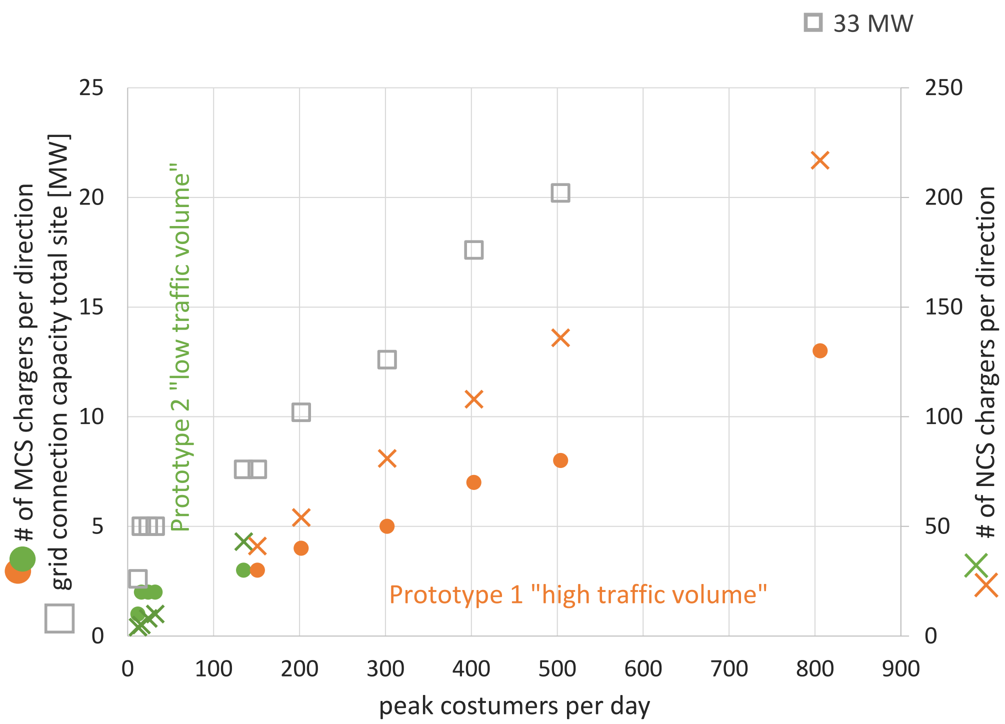


Figure 3: **Required number of MCS and NCS chargers per driving direction and total grid connection capacity for both directions related to the maximum number of MCS customers, orange: “high traffic volume” (prototype 1), green “low traffic volume” (prototype 2)**

Running the simulations, various charging strategies have been applied which allows to reduce the peak load at the grid connection point, without compromising customer satisfaction. The results show that – for the given ratio between MCS and NCS – the total grid connection capacity does not need to exceed the installed power of the MCS chargers.

Logistics hub (prototype 3)

As a **prototype for a logistics hub,** we consider a mixed business area with a size of about 125 hectare (ha) net. The traffic profile combines long-haul transportation with urban and regional distribution. Battery-electric short-haul (BE-SH) trucks will be introduced earlier than BE-LH trucks. Initially, they will determine the charging needs. For that reason, the analysis for this prototype is restricted to a high penetration (2040) scenario. Traffic intensities are 23.9 BE-SH trucks and 8.6 BE-LH trucks per business day and ha.

A large share of heavy trucks is leaving the hub one or two hours after arrival, after loading and unloading goods. In case of BE-SH and BE-LH trucks, these periods dictate the time windows for charging. This, together with the traffic intensity and its distribution over the day, determines the required number and capacity of HPC chargers.

The energy required for charging both, BE-SH and BE-LH trucks, is about 6.7 MWh per ha per day. For BE-LH trucks, we estimate that, during the peak hour, up to 15% of the daily vehicle fleet stays at the area. Due to the generally short stay of BE-LH trucks, this figure translates directly into their peak load. The rest period of BE-SH trucks is distributed over a much larger range and longer periods regularly occur. The peak load caused by the total truck fleet is estimated at about 500 kW/ha net business area.

For the considered prototype, the demand can be satisfied by 150 public HPC (@ 0.45 MW) plus 500 public NCS (@ 0.1 MW), connected to the grid via more than 100 compact MV/LV stations (distribution transformer cabinets). This on-site infrastructure requires a total grid capacity of about 60 MW and, hence, a connection to a HV substation. Larger logistics hubs will need even stronger grid connections.

Economic performance

For the set of assets, their specific investments and lifetime, annual depreciations can be calculated and related to the energy provided for all prototypes and scenarios. This allows a comparison and evaluation of the viability of the infrastructure represented by the prototypes.

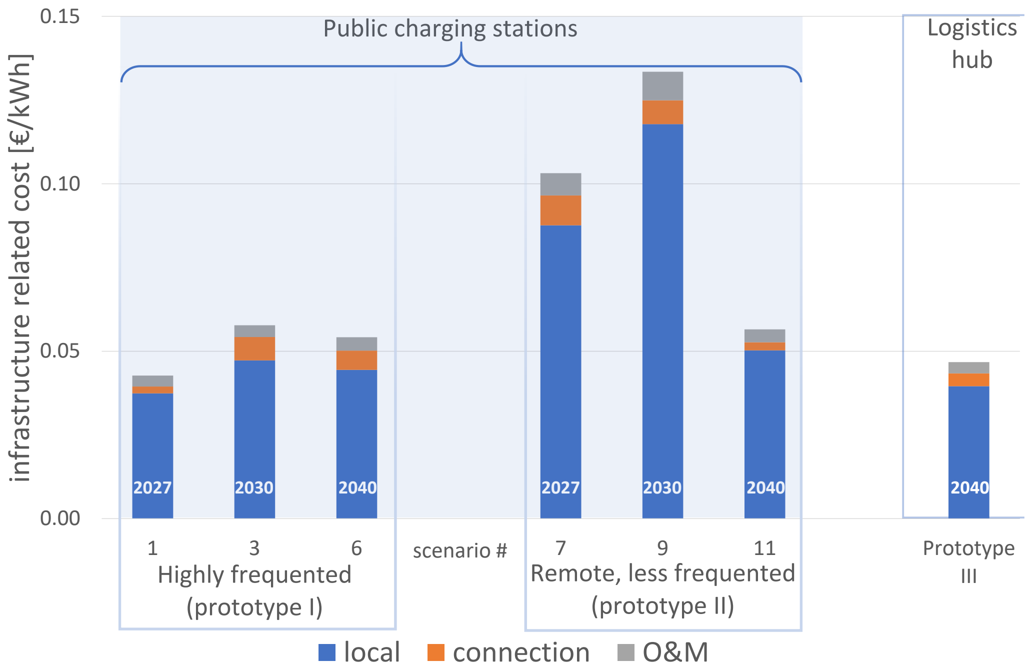


Figure 4: Overview of specific monetary value of infrastructure investments per kWh charged for the various prototypes and selected scenarios

The specific costs of prototype 3 (commercial logistics hub) in Figure 4 include the depreciation for the NCS serving BE-SH trucks.

The chargers represent the major share of the investments as well as the specific costs indicated as 'local' in Figure 4, in most cases 90% or more of the total. Any extension of their lifetime or a reduction of the specific investments (in terms of € per kW) helps to improve the economics of charging infrastructure for BE-LH trucks.

Due to regulated allocation and socialisation of network costs, the results of the analysis are not suitable as a basis for assessing the economic viability of individual projects. Instead, they allow for the evaluation of the societal costs of the infrastructure and for the comparison of related policy options.

Additional options for grid connection planning

We briefly assessed the viability and benefits of on-site stationary battery storage and combination with on-site PV generation at logistic hubs. In general, the integration of stationary battery storage systems is, regarding the analysed combination of MCS and NCS chargers, not beneficial and is in competition with the (much cheaper) charging management. In contrast, charging stations with a focus on MCS might benefit from storage systems. Economic benefits of on-site PV generation are limited. Deploying potential synergies will be challenging due to institutional complexity and the difficulty to synchronise planning and implementation of infrastructure.

Technology is still progressing. The introduction of local DC-distribution networks together with dedicated chargers offers a cost reduction potential compared to the presented findings.

Table of Contents

List of acronyms

BE-LH	battery-electric long-haul [truck]
BE-SH	battery-electric short-haul [truck]
GVW	gross vehicle weight
HPC	high-power charging system
HV	high voltage (e.g. 110 kV or 132 kV)
LV	low voltage (up to 1 kV)
MCS	megawatt charging system
MV	medium voltage (e.g. 10 kV or 20 kV)
NCS	overnight charging system
SoC	state of charge

1 Introduction

1.1 Motivation and scope

Direct electrification is one of the possible ways to decarbonise the road freight sector. Battery-electric trucks are one of the technology options being discussed. A precondition for battery-electric traction is the availability of a sound and reliable charging infrastructure. Power of charging stations as well as their density and location must meet the requirements of present and future logistics processes.

This report focuses on battery-electric long-haul trucks (BE-LH trucks), more specifically the respective charging infrastructure which will be required to make this development happen. Daily trip distances of the considered 40-ton tractor-trailer combinations are typically 400 km and more.[2]

The introduction of battery electric short-haul trucks (BE-SH trucks) in the urban and regional delivery segment will be less challenging. Due to the limited action radius, smaller and thus lighter battery packs are sufficient and charging power is lower. Looking at long-haul transportation, development will first focus on corridors, notably the TEN-T core network, but the extension of the infrastructure, even in the introduction phase, will need to cover complete EU member states. For all vehicle segments, it should be expected that battery electric trucks and the required infrastructure will be introduced gradually by prioritising their initial roll-out around geographical clusters which offer favourable techno-economic conditions and account for larger shares of road freight activity.

---

[2] We define long-haul trucking as freight movements on single vehicle trips longer than 400 km. Long-haul tractor-trailers will require a larger onboard battery for a minimum daily range of around 500 to 800 km and in a few cases more than that. In the EU, 78% of the road freight activity (in tonne-kilometres) is performed on trip distances of up to 800 km [24].

High-power and megawatt (MW) charging stations for long-haul trucks and their grid impacts are, unlike charging infrastructure for passenger cars, not well investigated yet. The principal design of an adequate charging infrastructure for electric long-haul trucks still needs to be analysed. Especially the charging power per charger, the necessary number of charging points per charging station and the typical usage profile are important for an understanding of the impact on the grid infrastructure. On top of that, the required investments in network connections and local assets for charging stations have to be evaluated. This is the set of aspects being addressed in this study. The outcomes can contribute to a sound comparison of battery electric long-haul trucks with alternative technology options, such as overhead catenary lines, hydrogen fuel cells or synthetic e-fuels.

1.2 Objectives of the study and approach

The objective of this study is to identify and to contribute to a better understanding of potential grid-related challenges of high-power and megawatt charging stations for battery-electric long-haul trucks (BE-LH trucks). The study shall evaluate configurations of power grid connections and their cost and examine potential barriers. Possible instruments will be reviewed which can help optimise the planning and roll-out of such high-power and megawatt chargers in Europe.

The design of a “universal” charging station is challenged by the fact that the duty cycles and mission profiles of long-haul trucks are in many respects diverse. Depending on the individual freight movements, trip distances, loading- and unloading times and driving shifts, the individual requirements for charging power, location and time can vary significantly. Accordingly, the charging infrastructure demand of long-haul trucks will in practice be very diverse, depending on the individual requirements of haulage companies.

However, charging opportunities can be generally broken down to

- Public high-power (HPC) and megawatt charging (MCS),
- (Semi-)public HPC and overnight charging (NCS) at the place of (un)loading of freight,
- Public NCS during longer rest periods, and
- Private NCS at the depot when the truck returns from single- or multiday travel.

A majority of charging processes of long-haul trucks will either take place at a public charging station or a commercial area, i.e. the place of (un)loading. In addition, long-haul trucks will also charge at the depot when returning from (multi)day travel.

In this study, we focused on (semi-)public charging and analysed three prototypes of charging infrastructure:

1) **Highly frequented public charging station (MCS and NCS)**
   A public charging station along the motorway network with intense long-haul traffic, representing the upper bound of public charging demands,
2) **Remote, less frequented public charging station (MCS and NCS)**
   A public charging station along the motorway network with minor long-haul traffic, representing the lower bound of public charging demands,
3) **Commercial logistics hub (HPC and NCS)**
   a medium-sized logistics hub with multiple haulage companies combining long- and short-haul trucks.

These prototypes can be considered as templates that illustrate the broad range of characteristics of long-haul charging infrastructure and thus allow a high transferability for further research.

We assess the techno-economic implications of the required charging infrastructure for BE-LH trucks dedicatedly and ignore expected synergies with parallel developments like charging of passenger cars at the same site. This somewhat academic approach is intentional. It allows to specify clear cases for comparison and delivers conservative results. In reality, infrastructure may be leaner and associated investments may be lower than found in our analysis.

Some important topics are intentionally not addressed in this study. These include, for example:

- General scenarios on energy and power system transition;
- external effects from other sectoral coupling trends and potentially conflicting policy objectives, e.g. the increased power demand due to the electrification of other sectors (buildings, industry);
- regulation of power markets and network development and policy instruments related to the introduction or stimulation of battery electric long-haul trucks;
- trends in electricity prices and their impact on the economic viability of this option;
- the potentially disruptive impact of the introduction of autonomous driving in the future.

We are aware that related questions are crucial for the described scenarios to materialise and that they have an impact on grid planning, potential connections or reinforcements. However, they are excluded from the scope in order to keep complexity manageable.

1.3 Structure of the report

In section 2, the general scenario framework is introduced. What are operational conditions of the trucking sector and how are they currently addressed at the service areas covered by the prototypes, even without any battery electric long-haul trucks? The needs are translated into key parameters, such as daily trip distances as well as the timing and duration of rest periods. Additionally, general design and rating conventions for network connections are introduced. The various types of charging terminals are specified.

This information serves as input for the scenario analysis in section 3. In this section, the requirements for the charging process are analysed, resulting from the given operational processes and assuming the increasing electrification of the trucking sector. Consequently, for the three prototypes, adequate network connections and charging terminals are derived and evaluated from a technical and economic perspective.

In section 4 we briefly assess three selected parallel developments with a potential impact on the scenarios:

- Benefits of (second life) stationary battery storage;
- Benefits of combining charging infrastructure at logistics hubs with local solar PV electricity generation; and
- Innovative topologies for chargers and the local distribution network on-site.

Finally, the findings and conclusions from the analysis and some key recommendations are summarised in section 5.

2 Scenarios

This section summarises the key input data for the modelling and analysis. On the one hand this input is based on existing studies and statistics dealing with road freight activity in the past, with a focus on the prototypes: motorway service stations and logistics hubs. These data points are combined with the penetration scenarios for battery electric long-haul trucks. This combination allows to derive requirements and framework assumptions for modelling[3].

On the other hand, the general assumptions for the design of network connections for the various capacity ranges are introduced and specified. These assumptions are translated into a limited set of configurations which will be applied in the analysis.

2.1 Framework of the analysis

The study analyses technical challenges and economic implications related to the charging infrastructure along the development path, starting from early adoption to high penetration shares of BE-LH trucks. We consider three different penetration rates of BE-LH trucks in the total long-haul truck fleet. These levels may be associated with the years 2027, 2030 and 2040.

The penetration levels differ from European averages and even per prototypical charging station due to various effects. Initially, numbers of BE-LH trucks will be limited. The early market uptake will be different across Europe. Even within individual member states, charging infrastructure will be first provided at some important motorways only. This will attract BE-LH trucks more quickly

[3] The data used as input for modelling and analysis are derived from German sources and, hence, reflect the current or recent situation in Germany. However, the illustrative scenarios built on these data, by nature, imply uncertainties. A reasonable interpretation of results allows to draw conclusions which are not specific to Germany but may be extrapolated to other European Member States and other regions of the European Union.

than elsewhere ("gravity effect"). Motorways with low traffic intensity will experience a lower share of BE-LH trucks. With increasing shares of BE-LH trucks, infrastructure will be rolled out across the regions and the gravity effect will become less pronounced. This will be similar at logistics hubs. However, in this case, when BE-LH trucks are being introduced, BE-SH trucks will have already affected the structure of the commercial area and created foundations for introducing BE-LH trucks as well.

Because of this heterogeneous and changing picture, the individual penetration levels are defined and introduced in the sections describing the prototypical charging stations.

With the emergence of BE-LH trucks, public charging stations will become necessary along the European trunk road network. Even in an early stage with low fleet penetration levels, the maximum allowable distance between charging stations at the highway will need to be limited, not only due to the expected vehicle ranges of BE-LH trucks but, more importantly, because of the EU Regulation on driving times and rest periods [1]. The rules foresee maximum daily driving periods of 9 hours (10 hours in exceptional cases) and minimum rest periods of (at least) 9 hours. In addition, mandatory breaks of 45 minutes every four and a half hours are legally required which can be split into two breaks of 30 and 15 minutes. These time windows will be used for recharging, at least to the extent that the vehicle can safely arrive at the next destination (including a reasonable safety margin). In the scenarios for the prototypical public motorway charging stations, we assume different average distances between charging stations, depending on the given year. Distances vary between 200 km (2027), 100 km (2027, 2030) and 50 km (2030, 2035 and 2040)[4].

Assumptions on the specific energy consumption of BE-LH trucks and resulting charging energy needs are specified in Table 7-1. The charging technology assumed in the analysis reflects the parameters being discussed in the ongoing standardisation initiatives

---

[4] An open letter of ACEA and T&E [23] demands a density of charging stations every 50 km, notably along the TEN-T core network until 2030 and is thus taken into account in this analysis.

[2]. The maximum power is more than one Megawatt (MW). Lower capacities are used for longer periods, e.g. overnight charging at dedicated areas along the motorway. Key assumptions characterising the chargers are summarised in Table 2-4 in paragraph 2.4.

2.2 Prototypes of public charging stations

The electrification of long-haul trucking will require different kinds of charging infrastructure, public, semi-public and private. In this section, we analyse the fundamental design of public charging stations and their evolution from 2027 to 2040.

Customer Volumes at Public Charging Stations

Prototypes 1 and 2 describe public charging stations along the European motorway network. As traffic flows can be very diverse, the prototypes are depicting a location with very high (1) and lower (2) traffic outcome. The analysis of prototypes is performed by means of the following analysis (see Figure 2-1). A detailed description of this approach can be found in sections 7.2 to 7.6.

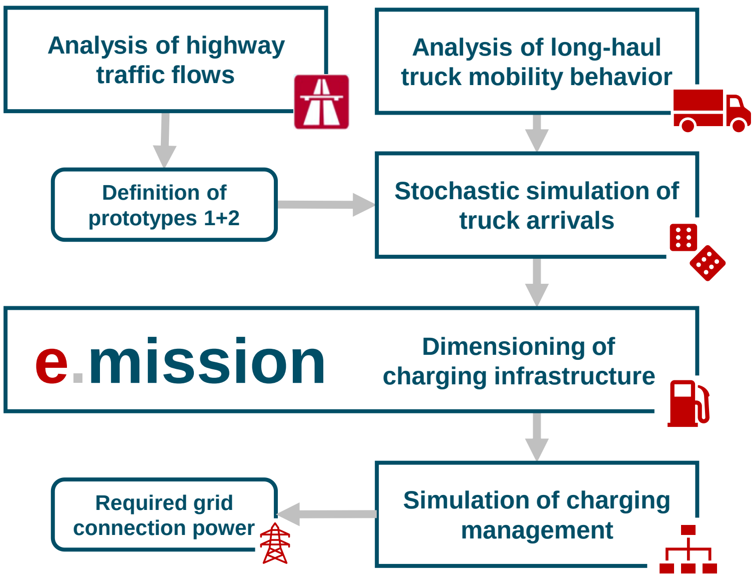


Figure 2-1: Analysis of public long-haul charging stations

In the first place, we analyse the traffic flows along the German motorway network and define the location of the prototypical charging stations. Figure 2-2 shows the average counting of heavy goods vehicles along the German motorway network, based on the automated traffic counting system [3][5].

Prototype 1 (“high traffic volume”) thus represents the upper bound of the expected traffic volumes until 2040, while prototype 2 (“low traffic volume”) describes the lower bound of considerable locations for charging stations.

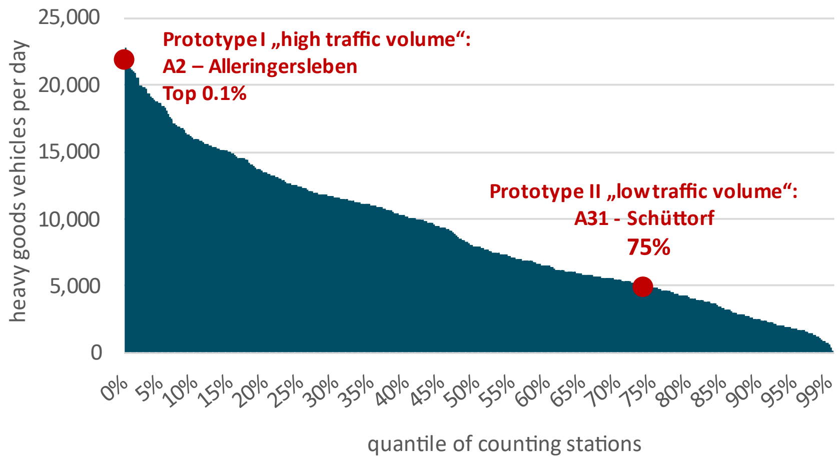


Figure 2-2: Daily average of heavy goods vehicles at German traffic counting stations on motorways (sorted)

Additionally, we consider a ramp-up scenario for these prototypes from 2027 to 2040 and – to a limited extend – a variation of the station density. Overall, this results in 11 scenarios of public charging stations (see Table 2-1). The share of BE-LH trucks among the truck fleet differs in times as well as between the two prototypes. For prototype 1 (“high traffic volume”), we assume a gravitational effect of the charging infrastructure: Initially, battery-electric trucks will primarily establish around local freight hotspots where charging infrastructure is deployed first. In contrast, prototype 2 (“low traffic volume”) reflects a local share of BE-LH trucks that lies slightly below the EU-wide average.

---

[5] A potential increase of the long-haul truck activity compared to 2018 is, with respect to the high uncertainty, disregarded. Interpreting the results, of course, this needs to be reflected.

Table 2-1: Prototypes and scenarios of public charging stations.

prototype	scenario	year	station density	share BE-LH
#	#	-	km	-
high traffic volume	1	2027	100	7.5%
	2		200	7.5%
	3	2030	50	20%
	4		100	20%
	5	2035	50	50%
	6	2040	50	80%
low traffic volume	7	2027	100	2.6%
	8		200	2.6%
	9	2030	50	7%
	10		100	7%
	11	2040	50	60%

In combination with the assumed ramp-up scenario of battery electric long-haul trucks, the two prototypes thus cover a broad range of possible customer MCS volumes (see Figure 2-1, details of the applied approach are described in section 7.3).

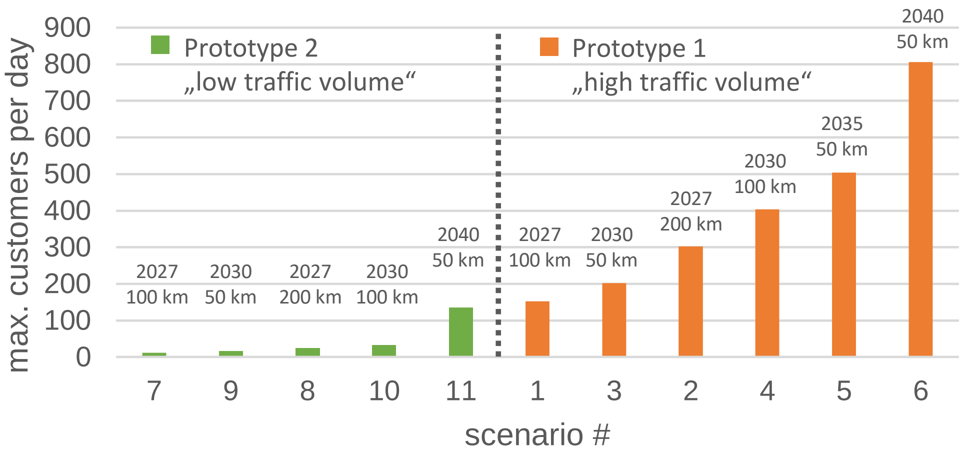


Figure 2-3: Maximum daily MCS customer volume

Besides the share of battery electric long-haul trucks, also the density of charging infrastructure is alternated within the scenarios. Thus, customers numbers in 2030 can be lower than in 2027 if simultaneously, the density of charging stations increases.

We assume the design of a public charging station to be similar to nowadays motorway service areas. MCS are offered at special stands that can be used for the duration of the charging process only. Overnight parking and charging is available at separate bays. Standing times are determined by the mandatory rest period and not by the duration of the charging process.

2.3 Prototype of a commercial logistics hub

Long-haul trucks regularly stay at business areas for loading or unloading goods. Business areas are diverse. They can range from some ha[6] to several hundred ha and the activities of companies may include logistics and warehouse distribution, industrial manufacturing, retail and entertainment. In this report, we focus on sites with logistics being the dominating activity.

The sites included in the European Freight Village Ranking have a size between some dozen ha to more than 600 ha with an average of 200 ha [4]. Typical traffic intensity is about one million trucks per 100 ha per year [5]. Assuming 250 working days per year, this corresponds to about 40 trucks per ha and average working day. This figure matches with general guidelines and reported traffic counting from two individual sites [6], [7].

As a prototypical example we consider an average logistics area with a size of about 125 ha net[7]. Out of the approximately 40 enterprises settled here, operational processes of about 20 companies are strongly linked to transportation, storage and distribution

---

[6] 1 hectare is 10.000 m^2.

[7] The physical area is larger (nearly 200 ha). It includes also commercially non-used area like greenfields, crossing water- and railways, etc. The ratio between gross and net area may differ substantially at different sites, also due to the different state of development.

of goods. The traffic profile combines long-haul transportation with urban and regional distribution (e.g. supply of supermarkets and shops in the urban agglomeration). For BE-SH, we assume an average round trip distance of 100 km, possibly several times per day. The share of long-haul trucks in the total number of trucks arriving at and departing from the area is assumed to be about 30%.

Traffic patterns, i.e. times of arrival and departure, typical duration of stays of the different shares of the truck fleet show an impressive diversity. Patterns depend on the character of the businesses. There is an obvious influence of the time of arrival and typical daily trip distances which are also correlated with the size of the trucks. Figure 2-4 illustrates different patterns of arrival and departure for two logistics areas and for trucks up to 12 tons gross vehicle weight (GVW) and above, respectively [7].

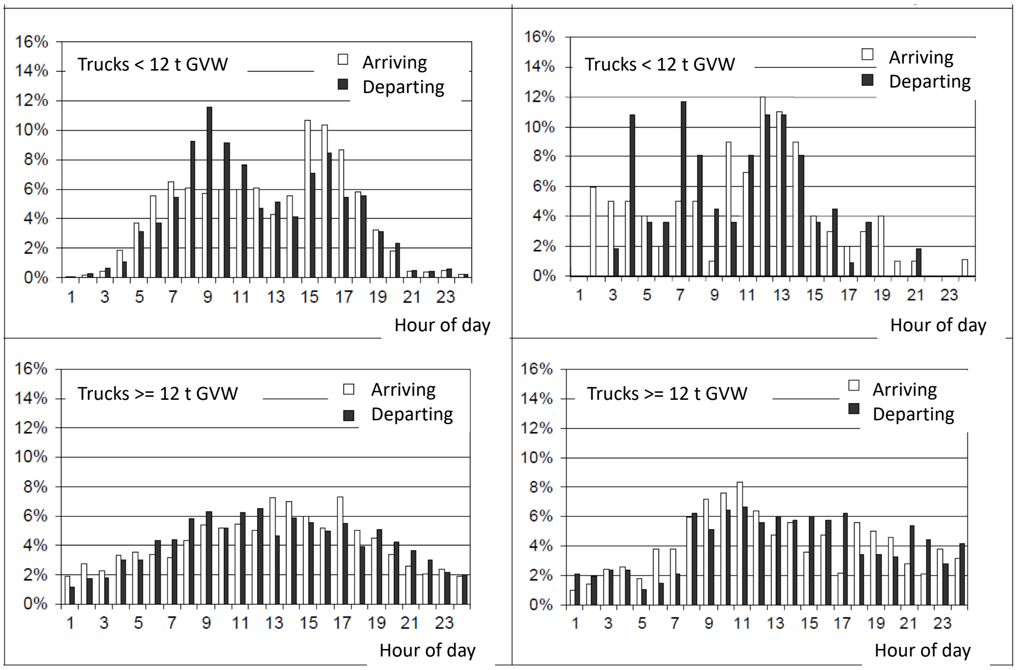


Figure 2-4: Arrival and departure of trucks at two different logistics hubs in the Hamburg area, Germany, hourly traffic share per direction in the daily total (countings during one single day); top: trucks <12 tons GVW; bottom: trucks >12 tons GVW, source [7]

Heavy trucks (>12 tons GVW) arrive during all times of the day, while lighter trucks (<12 tons GVW) arrive or departure the area during night-time only to a limited extent. An analysis of the data suggests a likely distribution of stays as illustrated in Figure 2-5. A majority of the lighter trucks is not operating during night-time and, hence, stay at the site during night for more than 5 hours. A significant share of all trucks is leaving within the first two hours after arrival.

These estimates are in line with the information gained in expert interviews [6], [8], [9] and are used in the further analysis.

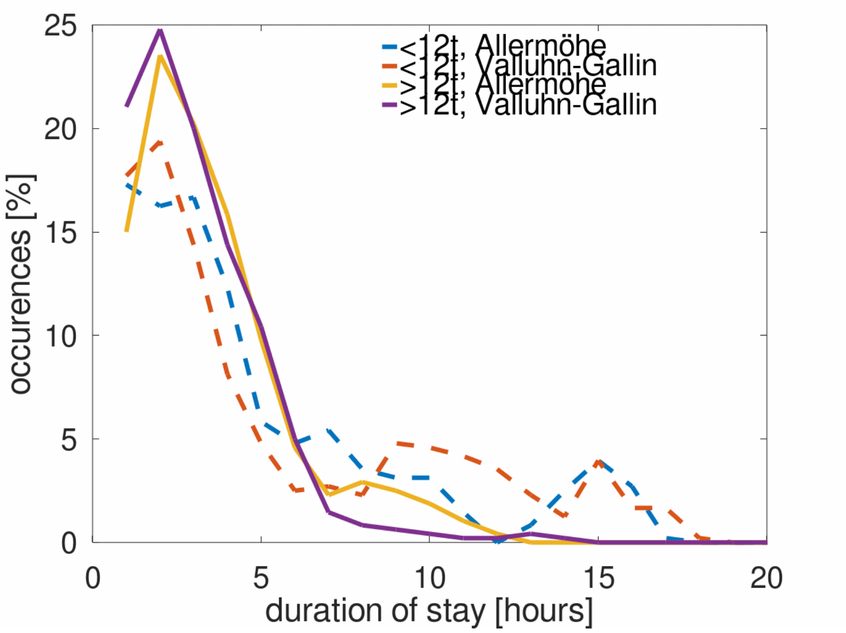


Figure 2-5: Distribution of duration of stays for two logistics hubs and trucks <12 tons GVW and >12 tons GVW, respectively[8]; own estimate based on [7]

In case of battery electric short- and long-haul trucks, the stays dictated by loading and unloading represent the time windows for charging their onboard batteries. It will not be tolerated that charg-

[8] Generating the distributions, the duration of stay has been binned in hourly intervals. This implies that in each bin also shorter periods occur. The power required for charging, hence, may be slightly higher.

ing negatively affects operational processes and therefore requires longer stays.

Due to lower range requirements, battery electric traction will be introduced earlier in short-haul distribution. Long-haul transportation in terms of fleet penetration will have a noticeable impact on charging infrastructure requirements starting from 2035. For that reason, in the analysis we consider potential challenges for a 2040 situation only. Reflecting the general scenario framework, we assume the following fleet characteristics and penetration rates of short-haul and long-haul trucks at the logistics hub.

Table 2-2: Assumed shares of battery electric short- and long-haul trucks at a prototypical logistics hub in a 2040 scenario

	Short-haul, regional distribution	Long-haul transportation
Specific number of trucks per ha and per business day (with peak traffic activity[9])	25.2	10.8 (30% of total)
EU average share of battery electric trucks in total truck population	54%	45%
Share of battery electric trucks at site, due to higher density regions and additional gravity effect due to infrastructure offered	95%	80%
Specific number of battery electric trucks per ha and business day (with peak traffic activity)	23.9	8.6

The introduction of battery electric trucks and their need for charging infrastructure will lead to some major structural changes at logistics hubs compared to the current situation. Currently, most logistics areas do not offer space for public truck parking. We assume dedicated, publicly accessible areas for parking and service on-site. These areas also offer the charging infrastructure. Tractors are parking there for charging after dropping the trailer at the cli-

[9] For the design case, we assumed 150% of average figures.

ent's bays. They return when the goods are loaded / unloaded and pick up the same or a different trailer for the next trip. Individual, private charging points per company would have major disadvantages: utilisation would be lower and, hence, costs would be higher. Simultaneously, the lack of public infrastructure would pose a barrier for the gradual introduction of battery electric trucks, in particular in case of external, third-party service providers. Hence, private charging at logistic hubs is not considered in the further analysis.

2.4 Network connection concepts

Connecting the charging points to the public power grid requires two kinds of grid: A connection to the public power grid as well as a local distribution grid in order to connect all chargers. Due to the large extent of a charging station, the analysis covers the costs for local distribution as well.

Local distribution grid

The large spatial extent of the charging stations and respectively logistics hubs will require a local distribution grid that connects the chargers. Because of the high connection power of the MCS, we presume a local distribution grid at medium-voltage (MV) level. MCS are connected to the MV-level with a distinct MV/LV transformer (1.5 MVA). The same type of transformer is used to connect 8 NCS to the local MV grid or 3 HPC, using a small LV grid (see Figure 2-6).

To account for the required demand for LV and MV power lines, the following blanked values are assumed:

- 25 m LV underground cable per NCS,
- 50 m MV underground cable per MV/LV transformer,
- 500 m MV underground cable for the interconnection between the two driving directions (public charging only).

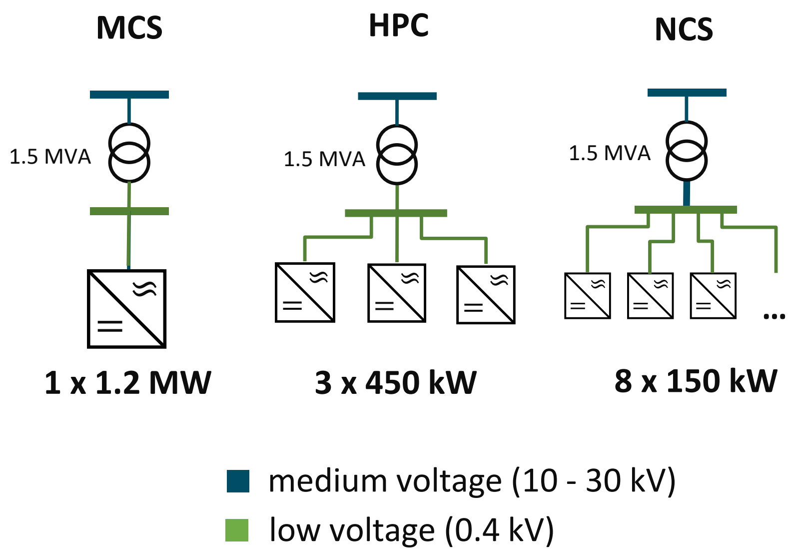


Figure 2-6: Grid connection of chargers

Connection to the public distribution grid

The different configurations of the public and commercial charging stations cover a broad range of grid connection power levels and thus require different grid connection concepts. In practice, the choice of the voltage level and the specific point of connection to the public power grid depends on numerous factors. Examples are:

- the available grid capacity of the pre-existing power grid infrastructure;
- costs of different connection alternatives;
- spatial and environmental aspects limiting the planning of potential routes, and potential public resistance;
- available space for potential locations of substations;
- construction costs and grid fees;
- anticipation of future peak power developments.

The design of the grid connection is thus always a trade-off between these potentially divergent factors and a universally valid concept does not exist. Nevertheless, and for the sake of simplicity, we assume the following universal grid connection concepts for all prototypes (see Figure 2-7):

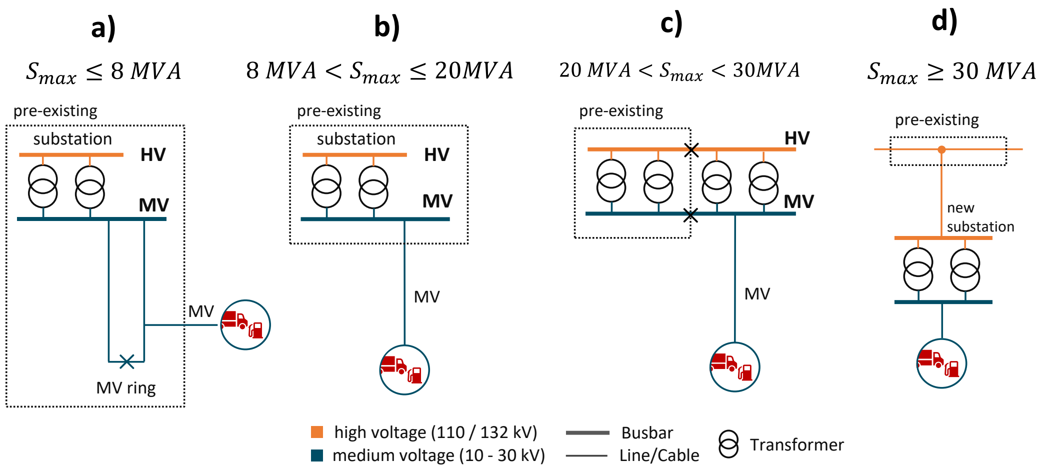


Figure 2-7: Grid connection concepts

Charging stations with a rated power below 8 MVA are connected to the closed medium voltage ring (a). Above 8 MVA, a distinct connection to the closest substation is established. If the pre-existing high voltage to medium voltage (HV/MV) transformers of this substation have sufficient reserve capacity, no further investment is necessary (b). We assume an available capacity of 20 MVA. Above this value, the addition of two HV/MV transformers becomes necessary (c). For values of 30 MVA and above, the charging station is directly connected to the HV grid (d). This involves the installation of a new substation, either in vicinity of the HV grid or the charging station.

Asset costs and lifetime

For a quantification of the total grid connection costs, a cost assessment of an extensive analysis of the German distribution grid is consulted [10] (see Table 2-3).

Table 2-3: Assumptions of required investments for grid assets and their lifetime, according to [10] and [11]

voltage level	asset	investments in k€	lifetime in years
LV	underground cable	60 / km	40
	transformer 1.5 MVA	25*	30
MV	underground cable	80 / km	40
	panel	70	25
	LV/MV transformer (40 MVA)	1000	25
	new substation	2500	25
HV	underground cable	800 / km	40
	overhead line (single conductor)	400 / km	40

*) own estimate

For the chargers we assume a lifetime of 8 years [12]. Investments are based on own estimates, bilateral exchanges and study results (see [13]) and are fixed for all scenarios, i.e. no change over time (see Table 2-4).

Table 2-4: Charging systems – key assumptions

charger type	MCS	HPC	NCS for prototype	
			1 and 2	3
charging power DC [kW]	1,200	450	150	90
rated power [kVA]	1,330	500	167	100
efficiency	95%			
investment [k€]	375	150	65	45
OPEX (1% of investment) [k€/a]	3.8	1.5	0.7	0.5
lifetime [a]	8			

For operational costs (OPEX) we assume an annual amount of 1% of the initial investment for all assets. This compares well to the current OPEX for DC chargers (see [12]) that lie between 0,6 % (350 kW) and 2 % (50 kW).

3 Techno-economic analysis

In this section we combine the general assumptions introduced before in our models. This allows to identify the demand for charging energy and power and, consequently, draw conclusions on the adequate network infrastructure to satisfy the needs. These technical figures are translated into the necessary investments for each of the prototypical charging stations. Finally, specific economic performance parameters (e.g. depreciation per kWh charged) are calculated and compared for the key scenarios.

3.1 Public charging stations

3.1.1 Demand for charging infrastructure

Megawatt charging systems (MCS)

Based on the customer numbers for all 365 days of the simulated year together with the developed truck mobility model, a flow of customers can be generated, which must be served by the MCS charging infrastructure in order to be dimensioned. The optimal number of megawatt chargers is determined by means of the simulation framework *e.mission* of ef.Ruhr (detailed description can be found in section 7.3). This model simulates the queuing and charging process of electric vehicle customers as well as charging management and restricted grid capacities. Within the model, we keep track of the share of served and unserved trucks. Trucks are considered as unserved, if the waiting time exceeds 15 minutes or if the target state of charge (SoC) cannot be reached within the break duration of 45 minutes. As often, it is not cost-efficient to target a share of 100 % served customers. This would result in extreme low utilization rates of the 'last' installed charger. We thus assume, that a cost-efficient number of MCS is given, if the share of served customers is 99% or higher. Accordingly, we tolerate longer waiting times for 1% of the customers during the peak traffic volume (e.g. before the Easter and Christmas holidays) as well as for random concentrations of customers for a limited extend.

Figure 3-1 shows the result of this analysis for all scenarios of prototype 1 and 2. For prototype 1 (“high traffic volume”), 3 to 5 MCS chargers are sufficient in 2027, depending on the density of charging stations along the motorway network. This number increases to 13 MCS chargers until 2040. As a rule of thumb, this corresponds to 50 to 60 customers per day per MCS charger, assuming the underlying *minimal charging strategy*[10].

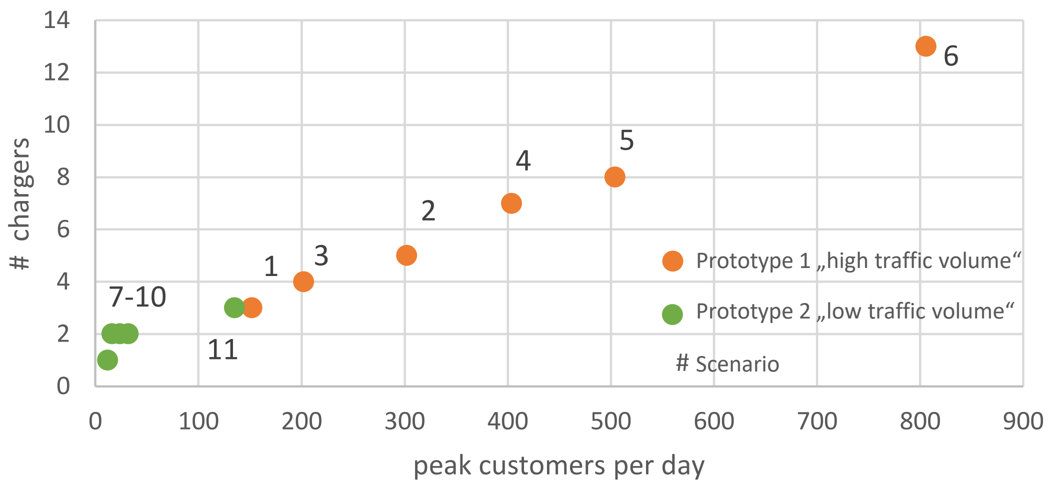


Figure 3-1: Minimal required number of MCS chargers per driving direction to guarantee a customer supply rate of 99%

For prototype 2 (“low traffic volume”), a single MCS charger is sufficient for 2027 (2 for lower station densities), while in 2040, 3 chargers become necessary.

Unlike charging infrastructure in other environments (e.g. private charge points), the simulations show that the MCS chargers require a grid connection capacity at the level of the installed capacity (see Figure 7-5). Only the 2040 scenario of prototype 1 (“high traffic volume”) shows a robust manifestation of the *law of large numbers,* which could allow a reduction of grid connection power

[10] This strategy assumes, that trucks have sufficient other charging opportunities, so that public charging is only necessary, if the trip distance is higher than the truck’s range. Additionally, trucks only charge the amount of energy that is necessary to reach the destination with a safety margin of 20 % SoC.

(without significant charging management) in this single scenario. However, this effect is not explicitly regarded. Instead, we investigate the possibility of overnight charging management in the further analysis.

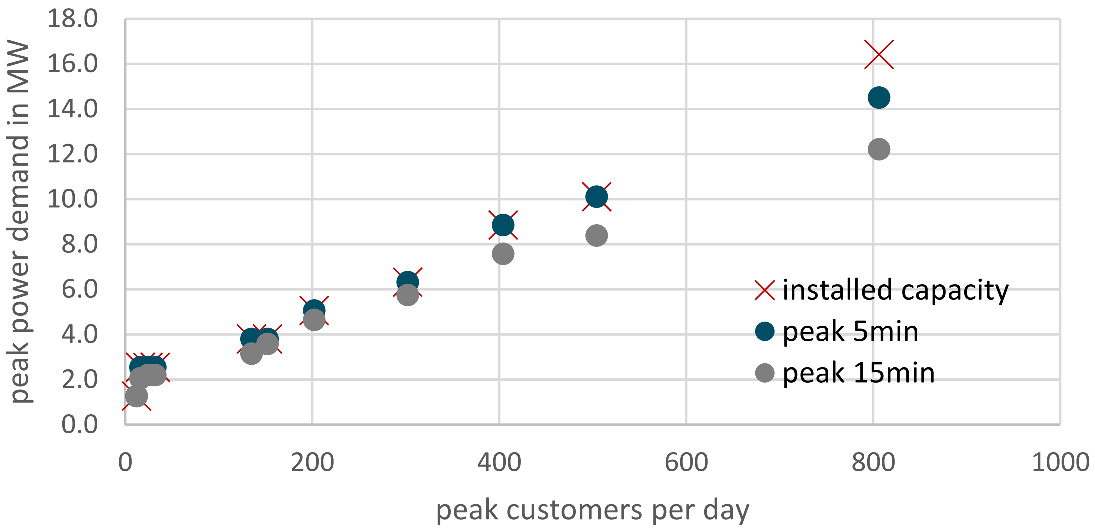


Figure 3-2: Peak power demand and installed MCS capacity per driving direction

Overnight charging systems (NCS)

BE-LH trucks, whose routes can involve multi-day intercity travel, will also need to rely on public overnight charging stations along the motorway network to charge during the mandatory rest period during the night. For an estimation of the required number of chargers, we assume that a similar density of overnight parking opportunities for trucks, as it is existing today, will be needed.

For a determination of today's existing overnight parking opportunities, we counted the available parking opportunities along the relevant motorway sections (BAB2 for prototype 1, BAB31 for prototype 2 in Germany). Together with the share of BE-LH trucks and the density of charging stations, we estimate the required number of overnight charging systems (NCS). This approach is described in section 7.3 in more detail. According to the tight dimensions of overnight parking opportunities (see [14] – many parking lots are currently undersized), we assume that during weekdays, all parking lots are used once per night.

The result of this approach is shown in Figure 3-3. Accordingly, the demand for NCS increases from 41 in 2027 to 217 in 2040 (prototype 1) and from 4 to 42 NCS (prototype 2) respectively.

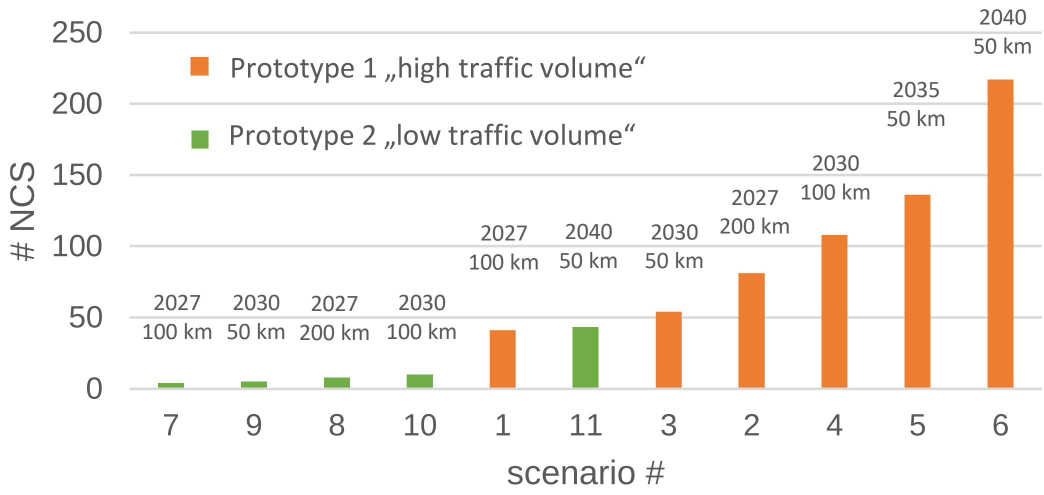


Figure 3-3: Required number of NCS per driving direction

The required number of NCS scales with the share of BE-LH trucks and as a function of the station density. Thus, a station might have a lower demand of NCS in 2030 than in 2027 if the station density of charging stations increases over proportionally more than the fleet share of BE-LH trucks.

Additionally, we simulated the temporal utilization of the NCS by means of the simulation framework *e.mission*. For this purpose, the same model is adjusted to the specifications of overnight charging. This involves:

- mandatory rest periods of 9 (resp. 11) hours,
- higher charging energies (trucks aim to completely recharge their battery),
- lower charging power of 150 kW.

With this configuration, the model reflects the challenges of overnight charging. Additionally, the model can analyse the potential of charging management, which is realised in the next step.

3.1.2 Network connection

Peak load and charging management

The previous analysis determines the minimal required number of chargers for the analysed public charging stations. We assume an efficiency[11] of the MCS and NCS of 95 % at maximum power output. To additionally account for a potential power factor below 1 and potential auxiliary equipment, the necessary grid capacity is dimensioned with a factor of 1.1 times the rated charging power.

The sum of the installed charger capacity (including the loss factor) could thus be used to determine the necessary grid capacity. However, MCS and NCS show very different profiles of utilization: The maximum customer volume of the MCS occurs at around 11 am, while for the NCS, most customers arrive at around 8 pm, resulting in a peak power demand of NCS at around 11 pm.

Thus, a charging management[12] approach enables a high degree of peak power reduction. According to the objective of fast charging, the MCS charging processes should not be affected, while the overnight charging processes feature high potentials for charging management. Additionally, the grid capacity must at least account for the installed capacity of MCS chargers anyway. We thus analysed the following charging management strategy:

- Charging processes of the MCS are prioritised and not affected.
- NCS charging processes can exploit the grid capacity to the extent which is remaining from the MCS utilization.
- NCS charging powers are reduced evenly among all charging trucks by means of a common factor.

The effect of this strategy is illustrated by scenario 4 (Figure 3-4): while the uncontrolled combination of MCS and NCS regularly exceeds the capacity of 8.8 MW, applying the charging management

[11] The main source of losses is the AC/DC converter.

[12] Charging management constitutes a dynamic reduction of the charging powers in order to distribute the peak demand over a longer period of time.

approach allows to keep the total power of MCS and NCS continuously below this value.

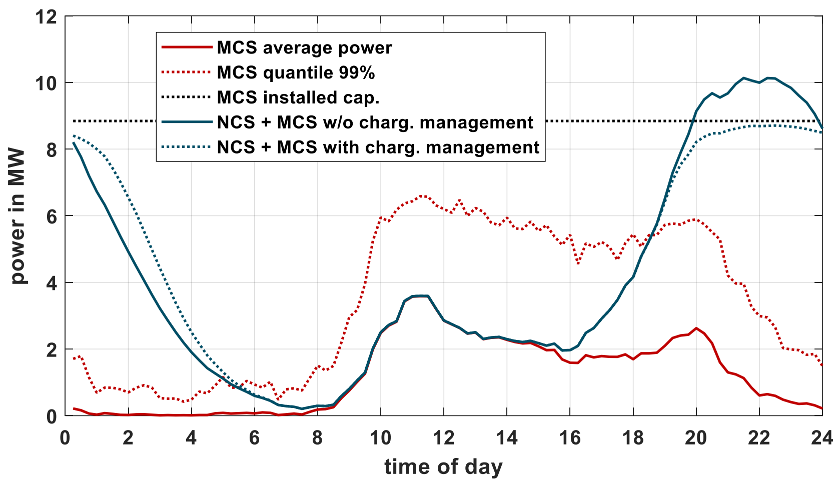


Figure 3-4: Average daily profile of power demand for scenario 4 (one driving direction)

The application of charging management raises the question if all overnight charging processes can be completed (i.e. is 100% SoC at the end of the rest period reached?). In fact, in all scenarios, this form of charging management does not jeopardise the objective to provide all trucks with a 100% SOC after their overnight rest period. Figure 3-5 exemplary shows the effect of different degrees of charging management on the SoC after 9 h of the rest period. In this scenario, the grid capacity of MCS is 9 MVA and the total grid capacity is pegged to this value. This results in a share of 100% of trucks, that are fully charged after 9 h. Negative effects on the trucks' SoC only occur at higher levels of charging management.

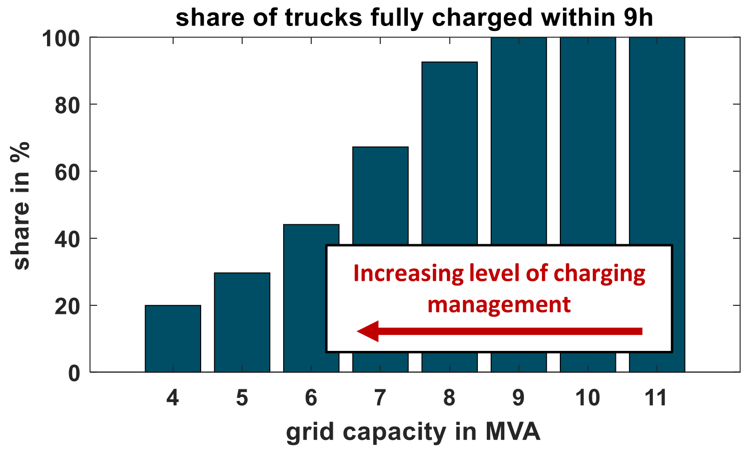


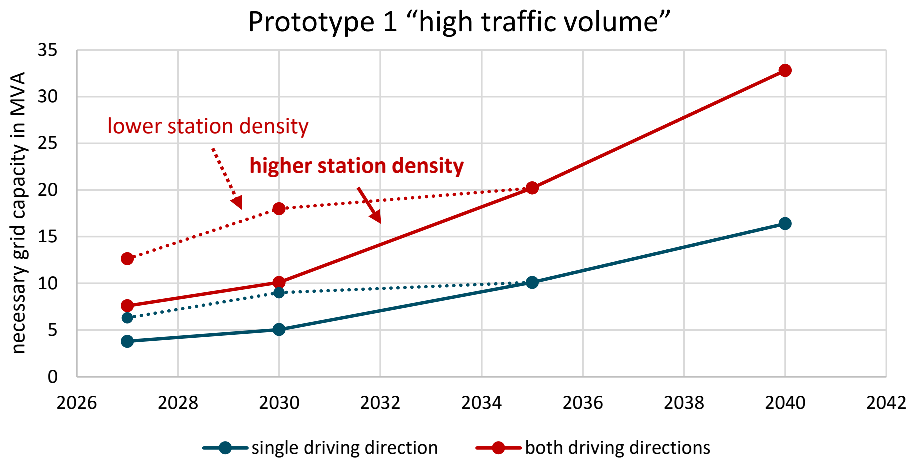
Figure 3-5: Influence of charging management on the share of truck which are fully charged after 9 (scenario 4)

Accordingly, the total grid capacity must – by means of the proposed charging management strategy and regarding the analysed ratio between MCS and NCS – account for the installed power of the MCS chargers only. There are thus high synergy effects between NCS and MCS and it is highly recommended to combine these charger types at one charging station.

Resulting configurations of network connections

Depending on the respective location and traffic volume, significant numbers of NCS and MCS will become necessary, together with the appropriate grid connection. Already in 2027, the required grid connection power can reach from 1.3 MVA for locations with low traffic volume, low shares of battery-electric trucks and a high density of charging stations to 13 MVA for busy locations and a combined supply of both driving directions (see Figure 3-6).

Following the further growth of the BE-LH truck fleet, the required grid connection increases significantly. For locations with high traffic flows, the overall grid capacity can reach up to 33 MVA in the 2040 scenario if the charging stations are installed on both driving directions.



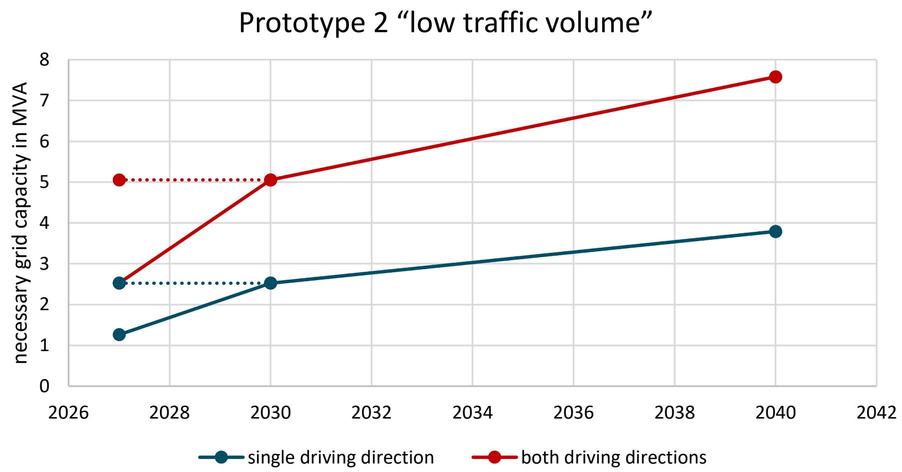


Figure 3-6: Development of the necessary grid capacity for prototype 1 and 2. Dashed lines depict scenarios with lower density of charging stations

At rural locations with less traffic volume, the total grid connection evolves from 2.6 MVA in the 2027 scenarios to 7.6 MVA in the 2040 scenarios (both driving directions). The scenarios with lower station density show that the station design can be kept constant if the increasing station density evolves proportionally to the increasing fleet share of BE-LH trucks.

Table 3-1: Required grid capacity of public charging stations (single driving direction)

proto-type # 	scenario # 	year -	station density km	MCS #	NCS #	grid capacity 1 dir. MVA	grid capacity 2 dir. MVA
high traffic volume	1	2027	100	3	41	3.8	7.6
	2		200	5	81	6.3	12.6
	3	2030	50	4	54	5.1	10.2
	4		100	7	108	8.8	17.6
	5	2035	50	8	136	10.1	20.2
	6	2040	50	13	217	16.4	32.8
low traffic volume	7	2027	100	1	4	1.3	2.6
	8		200	2	8	2.5	5.0
	9	2030	50	2	5	2.5	5.0
	10		100	2	10	2.5	5.0
	11	2040	50	3	43	3.8	7.6

Based on the design considerations described in paragraph 2.4, the capacities can be translated into the following network configurations. Scenarios, that are not explicitly listed, require grid connection concepts of the preceding scenario. We assume that a grid connection covers both driving directions. Compiling the final results, hence, the required grid connection capacity is twice the value presented here.

Prototype 1 – high traffic volume

Scenario 1 (2027): maximum load two times 4 MW, direct connection to the next existing MV ring (assumed distance about 2 km)

Assets on site per direction:

- 3 MCS (@1.2 MW), 41 NCS (@ 0.15 MW)
- 8 compact stations (distribution transformer cabinets)
- Identical grid connection concept for scenario 2

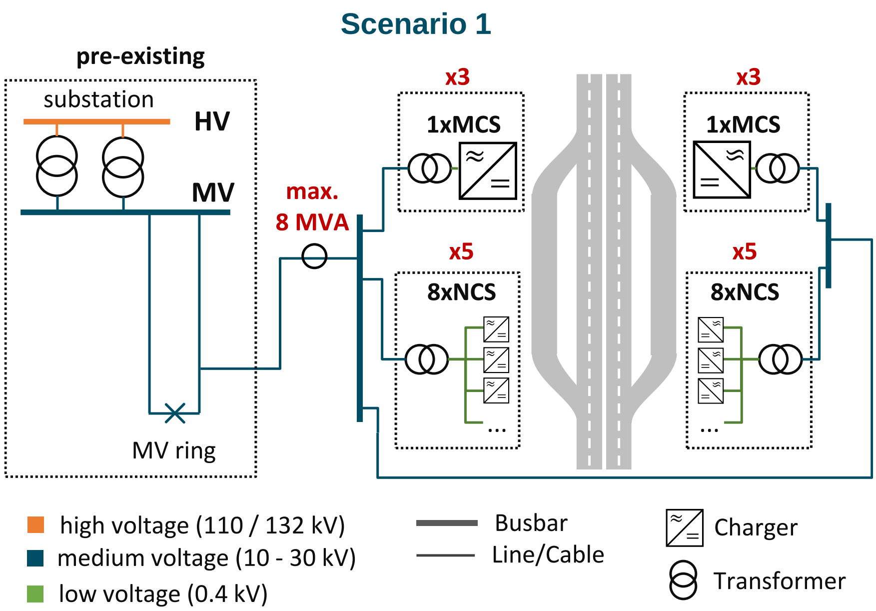


Figure 3-7: Configuration of public charging station at motorways with high traffic intensity, peak load 4 MW per driving direction (scenario 1 – 2027)

Scenario 3 (2030): maximum load two times >5 MW, separate line to existing MV station / busbar (assumed distance approximately 12 km)

Assets on site per direction:

- 4 MCS (@1.2 MW), 54 NCS (@ 0.15 MW)
- 11 compact stations (distribution transformer cabinets)
- Identical grid connection concept for scenario 4, 5

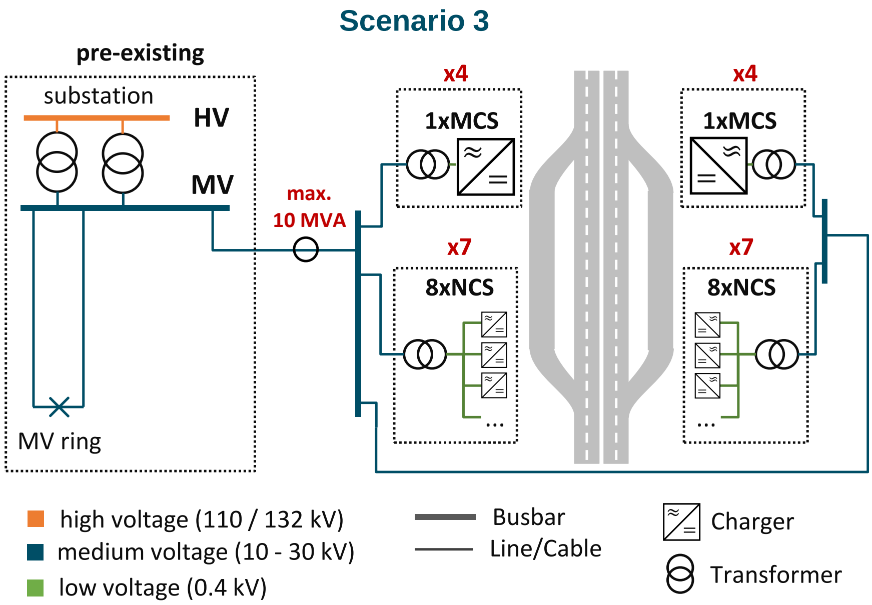


Figure 3-8: Configuration of public charging station at motorways with high traffic intensity, peak load > 5 MW per driving direction (scenario 3 – 2030)

<u>Scenario 6 (2040)</u>: maximum load two times 16 MW separate line to existing HV network, separate substation; assumed distances two options:

- A) Closest distance HV: 1 km @HV (likely overhead line), 12 km @MV (underground cable)
- B) Closest distance MV: 12 km @HV (likely underground cable), <0.5 km @MV (adjacent to area, underground cable)

Assets on site per direction:

- 13 MCS (@1.2 MW), 217 NCS (@ 0.15 MW)
- 41 compact stations (distribution transformer cabinets)

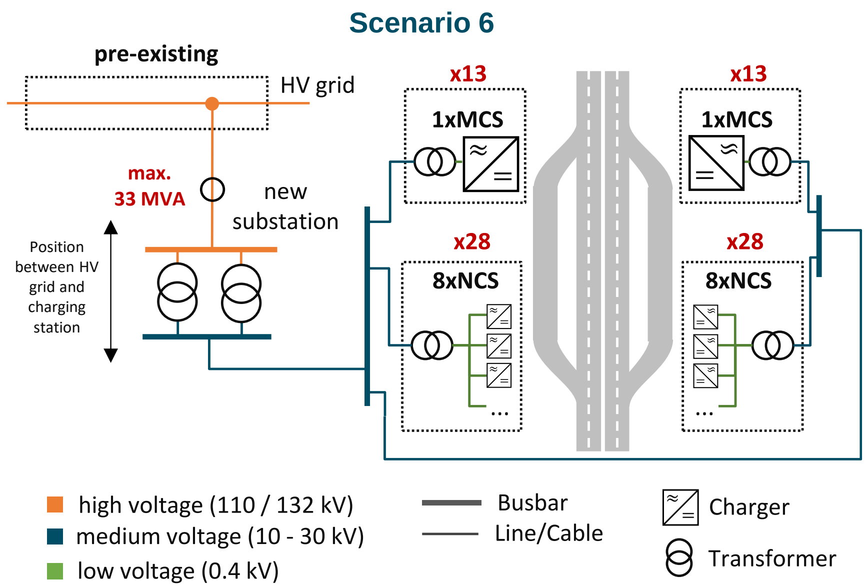


Figure 3-9: Configuration of public charging station at motorways with high traffic intensity, peak load 16 MW per driving direction (scenario 5 – 2040)

Prototype 2 – low traffic volume

Scenario 7 (2027): maximum load two times 1.3 MW, direct connection to the next existing MV ring (assumed distance about 2 km, general configuration identical to Figure 3-7)

Assets on site per direction:

- 1 MCS (@1.2 MW), 4 NCS (@ 0.15 MW)
- 2 compact stations (distribution transformer cabinets)
- Identical grid connection concept for scenario 8

Scenario 9 (2030): maximum load two times 2.5 MW, direct connection to the next existing MV ring (assumed distance about 2 km, general configuration identical to Figure 3-7)

Assets on site per direction:

- 2 MCS (@1.2 MW), 5 NCS (@ 0.15 MW)
- 3 compact stations (distribution transformer cabinets)
- Identical grid connection concept for scenario 10

Scenario 11 (2040): maximum load two times 3.8 MW, separate line to existing MV station / busbar (assumed distance approximately 12 km, general configuration identical to Figure 3-8)

Assets on site per direction:

- 3 MCS (@1.2 MW), 43 NCS (@ 0.15 MW)
- 9 compact stations (distribution transformer cabinets)

The identified configurations and number of assets are the input for the economic performance evaluation (paragraph 3.3).

Evolution of grid connection concepts

Along with the ramp-up of BE-LH trucks, the required grid connection power of public charging stations will increase gradually. For charging station and grid operators, this raises the question if grid connection capacities should be expanded simultaneously, or instead be "stockpiled" according to a given ramp-up scenario.

In practice, the connection concepts a) of Figure 2-7 can comparatively easily be transferred into concept b) if sufficient MV cables are installed in the first place and the additionally required cables can follow the route of an existing MV ring. Given sufficient available space in the HV/MV substation, the connection can be extended to concept c). In this case, a gradual extension of the grid capacity has no severe disadvantages compared to choosing concept c) from the start. In contrast, the step from concept c) to concept d) (HV grid connection) is rather big and requires substantial reconstruction measures.

As a consequence, an adequate planning of the grid connection should consider future upgrades of charging stations. A high predictability of the specific numbers of BE-LH trucks thus reduces the grid connection costs over time and reduces additional costs from misplanning. However, the rather easy expansion effort from low connection capacities to power levels up to 30 MVA provide a comparatively error-tolerant ramp-up phase during the next 15 years, even for the busiest locations.

3.2 Commercial logistics hub

3.2.1 Demand for charging infrastructure

The timing and duration of stays for the different truck categories have been estimated in section 2.3. This information, together with the operational parameters of truck flows allows to derive some representative parameters related to charging for the high penetration scenario (2040[13], see Table 2-2).

Table 3-2: Estimated, specific parameters for the logistics hub, high penetration scenario (2040)

	Unit	BE-SH	BE-LH
Average specific energy consumption plug-to-wheel[14]	kWh/km	1.14	1.26
Minimum range to be provided by charge during stay	km	80	360
Required capacity of chargers	kW	90 (NCS)	450 (HPC)
# of BE trucks (one direction) per day and per ha net business area, conservative guess: 150% of annual average	#/(ha·d)	24	8.6
Daily charged energy	MWh/ha	2.7	3.9
Resulting power in case of completely levelled profile (constant 24 hours a day)	MW/ha	0.11	0.16

The energy required for charging both, BE-SH and BE-LH trucks, is about 6.7 MWh per ha per day, resulting in an average load of 0.28 MW/ha.

---

[13] As explained in paragraph 2.3, earlier scenario snapshots are omitted because infrastructure requirements will be very much dominated by short-haul trucks. These, however, do not represent the focus of this study.

[14] This includes charger efficiency losses.

The required capacity of the network connection depends on the maximum number of trucks which are charging simultaneously, in combination with their respective rest period. For BE-LH trucks, we estimate that, during the peak hour, up to 15% of the daily vehicle fleet stays at the area. Due to the generally short stay of BE-LH trucks (see Figure 2-5), this figure translates directly into the peak load. The rest period of BE-SH trucks is distributed over a much larger range and longer periods regularly occur. Based on these estimates and parameters, we derived potential load profiles for the two examples introduced in section 2.3, illustrated in Figure 2-4 for the complete truck population. The bands in Figure 3-10 indicate the variation depending on the shares of BE-SH and BE-LH trucks, respectively.

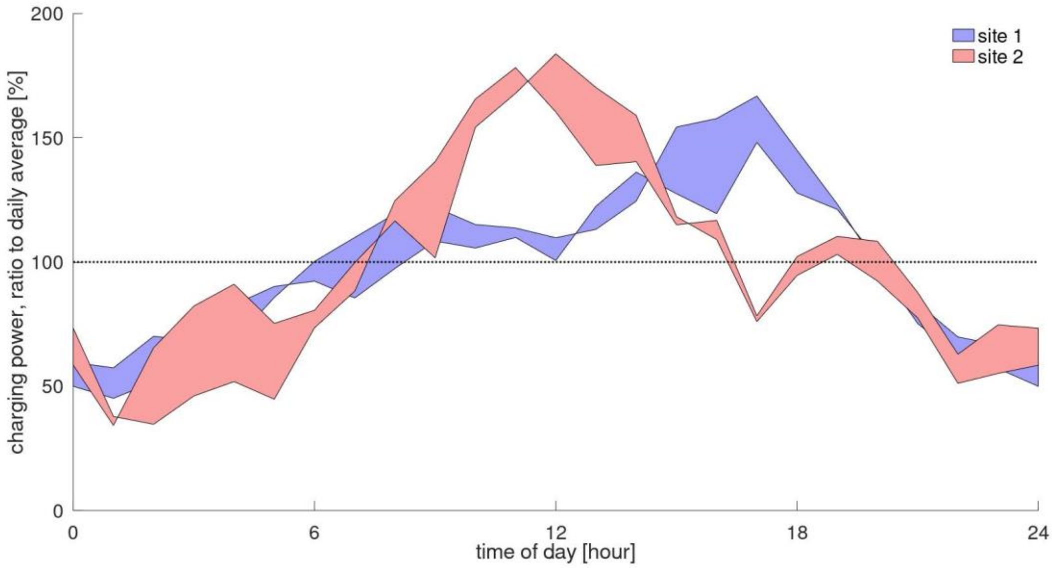


Figure 3-10: Estimated daily load profiles of battery charging for two prototypical charging stations at the logistics hubs with different traffic flow patterns and truck fleet composition; power normalised to perfectly levelled load (i.e. constant power over 24 hours)

The figure shows that the peak demand occurs at different times of the day, depending on the character of the business area. The peak load, in both cases is less than twice the value associated with perfect load levelling. 175 % of the daily average seems to be a robust guess. This results in a total peak capacity of about 500 kW/ha net business area.

3.2.2 Network connection

Current peak load levels of logistics areas are about 40 kW/ha [6]. Introduction of BE-SH and -LH trucks and their charging infrastructure will thus lead to an increase of the peak load by a factor of about 10. This demand cannot be satisfied by minor modifications to today's existing connection. A complete redesign and implementation of a new network connection will be required.

The logistics hub introduced in paragraph 2.3 has a net business area of about 125 ha. The results of the analysis above imply a connection capacity 60 MW and, consequently, a dedicated HV substation. Planning, permitting and construction of substations and HV lines usually takes several years. Therefore, the preparation and rearrangement of affected business areas and their power supply concepts has to start well before the need materialises.

In case of significantly larger areas, a direct connection to the transmission networks may be required. In most cases, large business areas are located in or close to urban agglomerations and, hence, distances to the transmission network are reasonably short (just for illustration see Figure 3-11). Nevertheless, strategic planning and sufficient lead times are even more crucial in these cases.

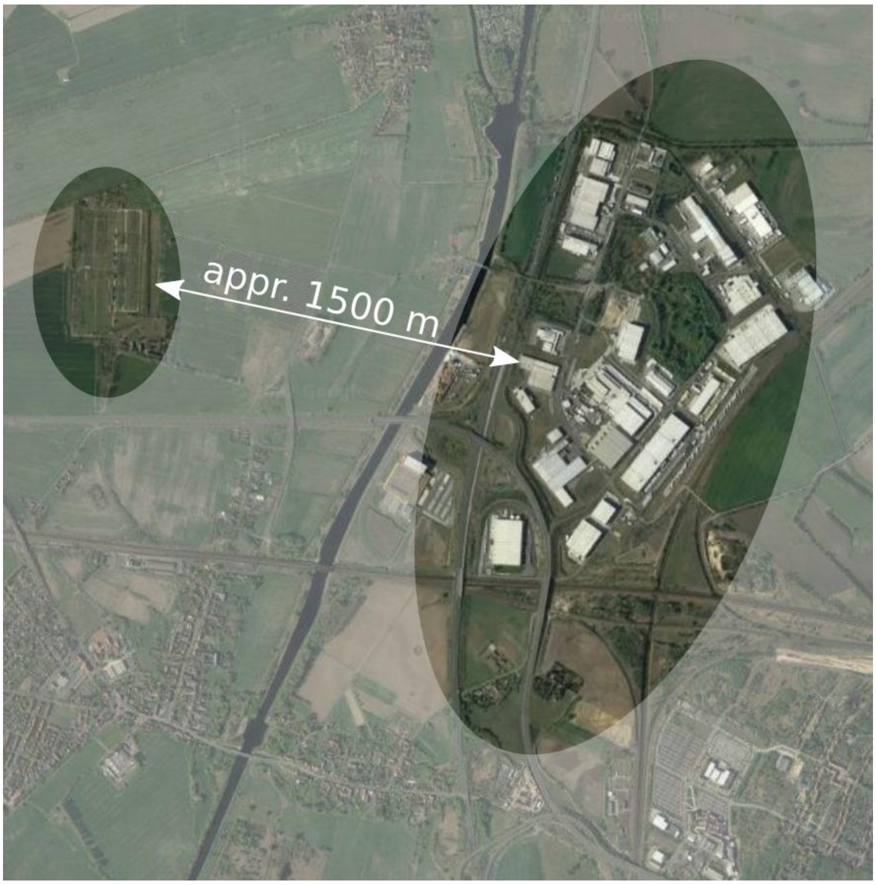


Figure 3-11: Logistics hub Wustermark, Germany (right) with nearby substation of extra high voltage 380 kV transmission network (left), source: Google Maps

The structural changes at the logistics hub itself ask for a strategic view as well. As described in paragraph 2.3, service areas for public parking and charging are required and the operation has to be managed. For the example site, we estimate that about 150 HPCs and about 500 NCS are needed. These chargers have to be accessible for drivers, regardless of the company they serve or belong to.

In our example, the connection of the prototypical logistics hub consists of the following elements:

Prototype III – high penetration scenario (2040): maximum load approximately 60 MW, dedicated HV substation with separate HV connection (assumed distance approximately 12 km)

Assets on site:

- 150 HPCs (@0.45 MW), 500 NCS[15] (@ 0.1 MW)
- 110 compact stations (distribution transformer cabinets – 3 HPCs and 10 NCS per transformer)

3.3 Economic performance evaluation

Based on the list of assets, their specific investments and lifetime, annual depreciations can be calculated for all prototypes and scenarios. (Some methodology aspects are discussed more in detail in the appendix 7.1).

The absolute value of the investments is not very informative – the prototypes are representative, but the variation of sizes and capacities between sites will be significant. Additionally, a comparison of investments does not allow to evaluate the economic viability of the options.

For that reason, we relate the annual depreciation plus O&M costs to the energy provided by the infrastructure[16]. This is the minimum contribution of users of the infrastructure required for refinancing the assets. Figure 3-12 shows the outcome of the analysis for some selected scenarios.

---

[15] The NCS serve BE-SH trucks. From a methodology point of view, in the other parts of the report this truck category and its infrastructure requirements are not considered in this study. In the course of the analysis of prototype III, a separation of these two categories, however, is impossible.

[16] The energy provided in prototype 1 and 2 can be found in the table in appendix 7.6. For prototype 3, the value is the average daily consumption as derived in paragraph 3.2.1, multiplied by 250 working days per year.

Logically, the specific infrastructure related costs are lower when more energy is provided with the same assets. For that reason, prototype 2 (“low traffic volume”), while requiring the lowest absolute investments in the starting phase (2027, 2030 scenarios), is associated with the highest specific costs.

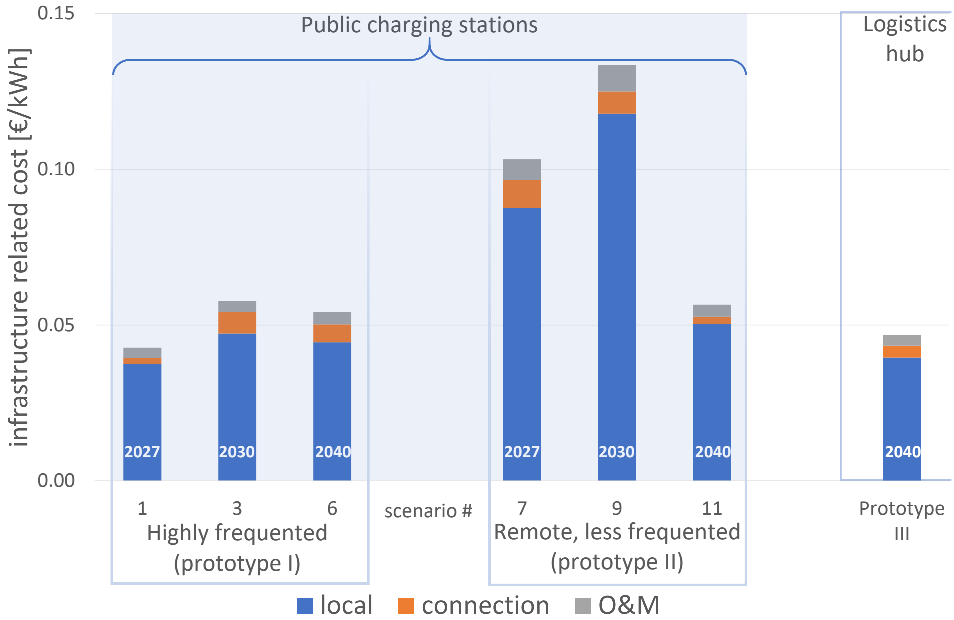


Figure 3-12: Overview of specific monetary value of infrastructure per kWh charged for the various prototypes and selected scenarios

Some remarks:

- As introduced in paragraph 3.1.2, depending on local conditions, there are two options to connect the charging station with the network: with a longer HV connection and a short distance at MV or vice versa. Figure 3-12 shows the first option. The investments for the alternative and, hence, the final cost result in the figure would be slightly lower.
- The specific costs of prototype 3 (commercial logistics hub) in Figure 3-12 include the depreciation for the NCS serving BE-SH trucks. Excluding the latter from the balance reduces the outcome.

The **chargers** represent the major share of the investments as well as the specific costs indicated as ‘local’ in Figure 3-12, in most cases 90% or more of the total. Any extension of their lifetime or a reduction of the specific investments (in terms of € per kW) helps to improve the economics of charging infrastructure for BE-LH trucks. Innovative technology concepts promising cost reduction potential, at least for moderate power ranges (NCS or HPC), are actively investigated ([15] [16], see, for example, paragraph 4.3).

The limited share of specific costs for the **network connection** may be somewhat misleading, due to the long depreciation period of the assets. In the case where the expected utilisation does not materialise during the technical life of the assets, the specific financial burden will be higher. Despite the lower share in the total investment, this risk is relevant because, unlike investments in chargers, incremental growth of the network connection is not possible.

The figures allow a mutual comparison of the scenario snapshots for the same year. It is, however, important to understand that the investments in network assets or related depreciations will not be seen by stakeholders. Cost allocation in the network industry very much relies on socialisation: connection and use of system charges do not reflect the exact costs caused by an individual connection. The charges are subject to regulation and our analysis completely abstracts from existing or future regulative frameworks. In other words: **the results of the analysis cannot serve as a forecast of infrastructure costs from an individual project's point of view and, hence, are not suitable as a basis for assessing a projects economic viability**. At a highly aggregated level, they are suitable for evaluating the societal costs of the infrastructure and comparing related policy options.

4 Additional options for grid connection planning

So far, we analysed the needs resulting from the scenarios, the network configurations required to satisfy these needs and the associated investments. These aspects were adequate for a quantitative assessment. However, developments related to the introduction of BE-LH trucks are embedded in a much broader policy framework. Driven by climate policies, including the European Green Deal and the European Climate Law, also other industrial sectors will increasingly convert their energy supply to electricity, whether directly or indirectly (power-to-X). The installed capacity of intermittent renewables will continue to grow and, accordingly, European transmission system operators (TSOs) will invest massively in their networks.

At the end of the scenario horizon, most likely second life batteries will be available for stationary storage at very competitive cost. On the other hand, autonomous driving may increase the utilisation of BE trucks and, hence, may help to justify extra investments.

Because of the variety of these, partly highly uncertain factors, their impact cannot be completely evaluated at the current stage. As illustrative examples two ‘case studies’ are considered here. The first elaborates on the potential synergies between the charging infrastructure for BE trucks and renewables. The second evaluates potential benefits of stationary storage. Additionally, we give an outlook on local DC grids and their opportunities and challenges.

4.1 Network connection in combination with stationary storage

Battery energy storage systems (BESS) can reduce the peak power demand of grid customers and may thus allow a reduction of the required grid connection power of charging stations. In this section, we analyse the potential of BESS for a reduction of the peak power demand and thus grid connection investments. Due to the high complexity, we focus the analysis on scenario 4 of prototype I only.

BESS dimensioning

In a practical implementation, a peak power reduction with BESS will, in case of a non-availability of the storage (due to failure or maintenance) always require a charging management system. A narrow (and thus by tendency more economic) dimensioning of the storage can thus interfere with the charging processes at peak times and thus has an influence on charging and waiting times as well as customer supply rates. Thus, a detailed analysis of narrow storage dimensions, which interfere with customer supply rates, involves a complex analysis including the previously introduced modelling framework *e.mission*. Alternatively, if the storage is sufficiently dimensioned and neither power nor capacity are limiting customers supply rates, the analysis can be based on demand profiles only. For the sake of simplicity, we focus on the latter option in this analysis.

Accordingly, the analysis is based on the individual demand profiles of the previously analysed scenarios. The power of the BESS is almost exclusively determined by the difference between the peak power demand of the chargers and the target grid connection power, while the capacity depends on numerous factors. These are:

a) the specific electricity demand profile,
b) the efficiency of the storage system,
c) additional mobility requirements such as back-to-back capability[17],
d) additional requirements due to a combination of use-cases.

For the sake of simplicity, we focus on a) and b) in this analysis. Further, we assume the parameters for utility scale stationary storage systems, shown in Table 4-1. The cost parameters are esti-

---

[17] „back-to-back capability“ originally describes the ability of a hydrogen filling system to consecutively refuel a specific number of vehicles in temporal proximity. This value is important for the dimensioning of hydrogen filling station but can also apply to battery-supported charging stations.

mates, based on the findings of [17] but split between power and energy.

Table 4-1: Technical and economic parameters of utility-scale stationary storage systems

Parameter	value	unit
round-trip efficiency	90%	-
investments 2030	100	€/kW
	175	€/kWh
investments 2040	75	€/kW
	140	€/kWh
lifetime	15	a
OPEX [18]	2.5 %	-

The required battery capacity can further be determined by simulations of the temporal behaviour of a hypothetical battery storage. An exemplary result of scenario 4 (highly frequented public charging station in 2030) is depicted in Figure 4-1. The figure shows the necessary battery capacity dependent on the intended peak power reduction as well as the resulting battery system costs.

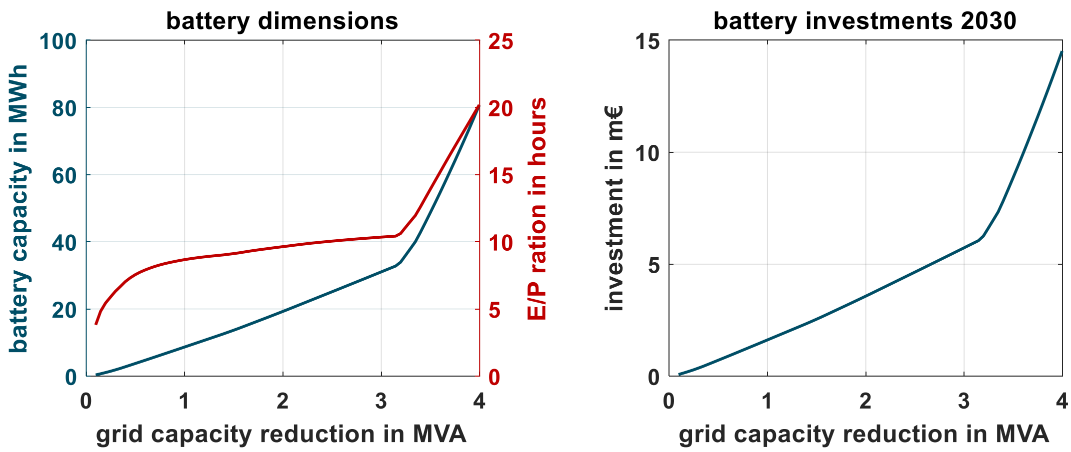


Figure 4-1: Required storage dimensions and costs for a peak power reduction after charging management (scenario 4, prototype 1 “high traffic volume”, 2030)

As can be seen from the E/P ratio (this equals the storage capacity in terms of hours), a significant reduction of the peak power demands requires a BESS with a E/P ration of up to 10 h. This value is unusually high for BESS in peak shaving operation and results in comparatively high storage costs.

The reason can be found in the underlying charging management of overnight charging processes: Due to the charging management, the load profile is already almost perfectly 'flat' between 7 pm and 2 am (compare Figure 7-11). A BESS must thus shift all power between night and day and cannot recharge in-between. Below a grid capacity of 5.8 MVA energy even needs to be shifted between weekends and weekday, resulting in even higher storage capacities which would be required.

Savings in grid connection costs

On the other hand, investing in a storage system can reduce grid connection costs as well as power-related network charges. However, especially the grid connection costs grow in discrete steps, which complicates a general assessment of the economic feasibility of a BESS. Additionally, the regime of network charges differs among (and sometimes also within) European countries. A general assessment of a battery's revenue side is thus not possible and depends on the individual conditions.

Figure 4-2 shows an exemplary analysis for scenario 4 (prototype 1, 2030). The left side of the figure shows the annualized costs of the grid connection (blue) and the annual grid fees (i.e. network charges, grey), dependent on the total power demand. Grid fees are based on the current tariff of *Westnetz*, the largest German distribution grid operator [19]. For scenario 4, annual costs of around € 1 million apply and can be reduced by storage application.

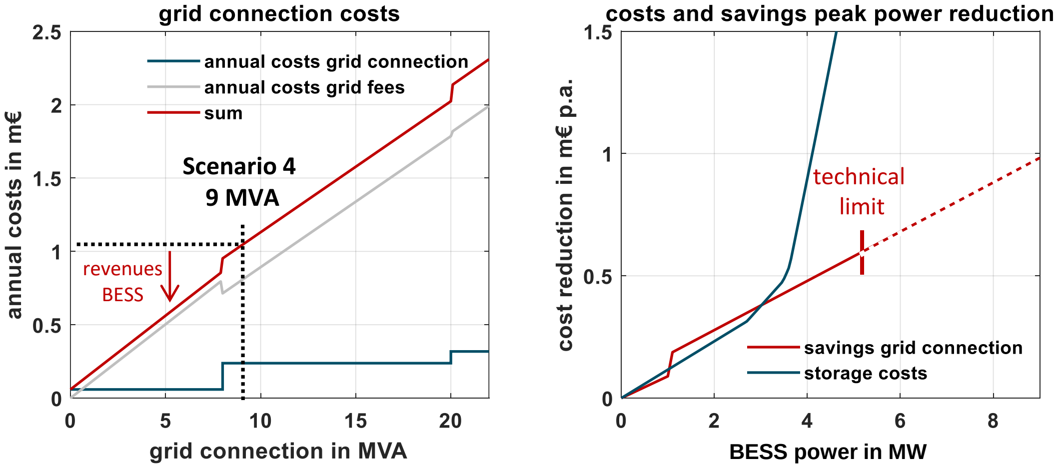


Figure 4-2: Annual grid connection costs subject to grid connection power (left); comparison of costs and revenues dependent on storage power (right)

The right side of the figure shows the resulting costs and revenues of different storage power levels. Small storage systems below 1 MW are thus not beneficial, since this power would not enable a smaller grid connection concept. For systems between 1.1 and 3 MW, the potential revenues exceed the annual costs, as these systems allows a connection to the pre-existing MV-grid. Higher battery power levels would not be profitable since they would require over-proportionally large battery capacities.

Spatial requirements for BESS are comparatively low. Stationary battery systems of this size are usually housed in 40 ft or 20 ft containers. Dependent on the E/P ratio, a single container can nowadays contain up to 5 MWh of energy (given low c-rates). Regarding the economic range of battery sizes (10 to 30 MWh), this corresponds to 2 to 6 40ft containers.

The comparison of costs and revenues of a single year are however less conclusive. During the ramp-up phase of charging stations for BE-LH trucks, the peak demand will be increasing steadily. A BESS can thus only delay grid expansion measures for a limited amount of time. This complicates the optimal dimensioning of the storage system and thus impairs any potential business case.

Battery Systems for MCS stations

Charging stations combining MCS and NCS show long-lasting peak power demands and are thus not ideal for economic BESS operation. However, charging stations that only provide MCS show a very different demand profile (see Figure 4-3, red line) with very short durations of peak power demands.

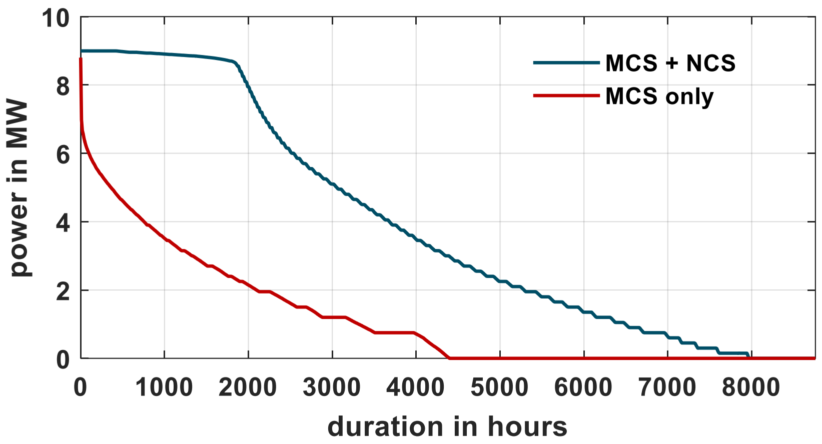


Figure 4-3: Duration curve at grid connection of scenario 4 (prototype 1 “high traffic volume”, 2030)

A peak power reduction thus requires comparatively low storage capacities, promoting a feasible economic application. As can be seen from Figure 4-4, a storage system with an E/P ratio below 1 h can be sufficient for a peak power reduction of almost 4 MW, requiring investments of less than € 1 million and thus less than 10% of the BESS investments for a station including NCS.

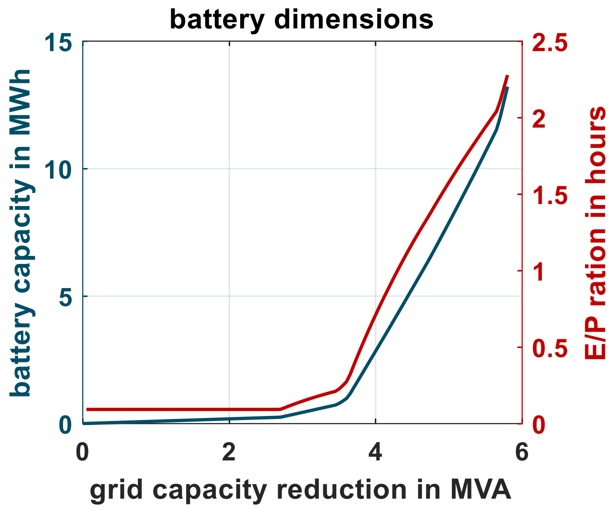


Figure 4-4: Required storage dimensions for MCS stations (scenario 4)

Additional Revenue Possibilities

In addition to the reduction of grid connection investments and network charges, a BESS can potentially generate revenues from additional use-cases. Examples are:

- optimising the own consumption of locally generated renewable energy,
- the optimisation of electricity procurement costs,
- the increase of a renewable energy supply, e.g. established by means of a PPA[18],
- the provision of ancillary services, e.g. power-frequency control,
- backup supply in case of blackouts.

However, the economic potential of these use-cases highly depends on the respective market conditions and the remaining idle time of the BESS and their predictability. Concepts combining different use-cases require an appropriate operational concept and are thus not investigated further here.

---

[18] A PPA („power purchase agreement“) is a contract between a producer and a consumer of electricity and allows a “virtual connection” to renewable energy sources such as wind energy farms.

Conclusion

The application of a BESS for BE-LH trucks can be an economically viable option, especially if it allows the delay of grid expansion measures. The benefit is, however, very individual and depends on the economic and technical circumstances as well as the development of traffic flows and peak power demand. Especially the dynamic evolution of the numbers of chargers (and the peak power demand) can pose a substantial challenge for an economic storage application. In cases, where the provision of a sufficient grid connection cannot be accomplished in time, BESS can work as an interim solution that guarantees high customer supply rates.

The analysis is focused on scenario 4, but the results will be similar for other scenarios and prototypes. Divergent results can be expected for charging stations with less than 2,500 full load hours. In this case, the German regime of grid fees offers significantly less incentives for peak shaving applications. This can be different for other European countries.

In contrast to charging stations combining MCS and NCS, charging stations with an exclusive focus on MCS show better preconditions for potential BESS applications. In this case, the battery does not compete with the (cheaper) charging management option and requires significantly smaller battery capacities. In addition, lower usage time favours the combination with other use-cases and can improve the economic feasibility and viability.

4.2 Combination with local renewable electricity generation

Logistics hubs represent areas of diverse commercial activity and may offer suitable conditions for the development of commercial renewable generation sites. In particular, rooftop areas of logistics companies and warehouses can be used for installing photovoltaic installations (PV). Respective synergies are already deployed (see aerial photograph of one of the logistics centres serving as reference for prototype III in Figure 4-5). Given suitable spatial conditions, also greenfield development of generation sites adjacent to the logistics hub may be an option.

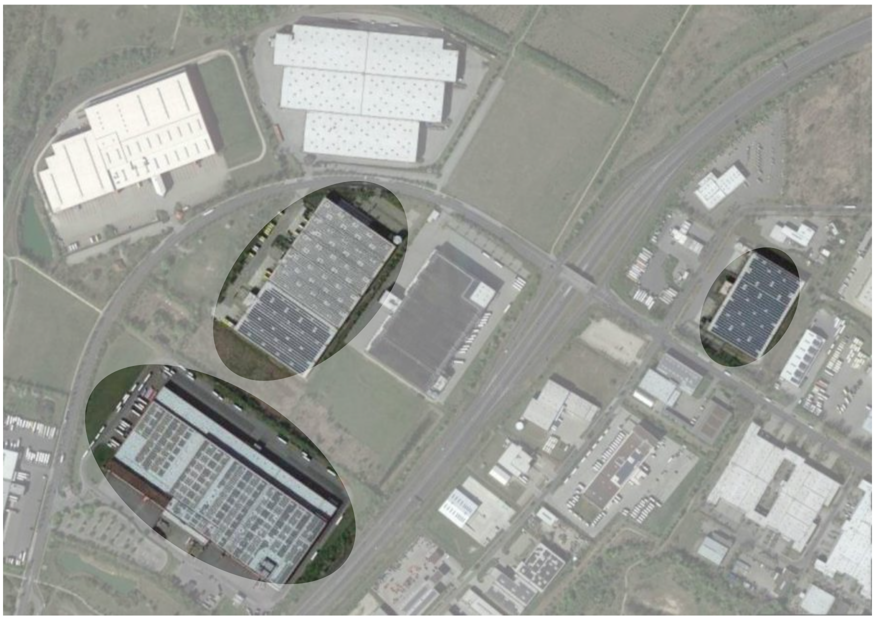


Figure 4-5: Part of logistics hub (Großbeeren, Germany), arial photo showing roofs of warehouses equipped with PV installations. Source: Google maps

As an illustrative example we assess potential benefits of a combination of PV with public charging of BE-LH trucks[19]. As in para-

[19] At some sites, a combination with wind power may be an option as well but this option is not discussed here. Planning and permitting are more complex and the wind yield potential is very much site dependent.

graph 3.2, we only consider a case with a high penetration of BE-LH trucks (2040 scenario). The general considerations are valid during the transitional period as well, the indicated figures will differ, though. In practice, the development steps may be the opposite from the reasoning applied below: it is likely that the growth of PV generation happens before significant shares of BE-LH trucks arrive at logistics hubs.

Adding PV generation to a logistics hub does not allow to reduce the grid connection capacity. PV will not reliably reduce peak load. Even in cases where the maximum load (regularly) occurs during the day, in winter PV generation will effectively not be able to contribute to load coverage.

Unlike stationary battery storage, the batteries of trucks generally will not be available for load balancing or other system ancillary services. The time window for opportunity charging is limited and operational flexibility is rather low.

The synergies of on-site PV generation and truck charging at logistics hubs are obvious and the technical implementation is straightforward. Nevertheless, deploying this potential will be challenging. In most cases, the development and operation of business areas as well as of electricity generation is done by different, in most cases independent business entities. Contractual and legal relationships may be complex. Collaborative allocation of cost and benefits in case of shared connections is only possible if timing of both developments is closely synchronised. This will rather be the exception.

Case 1 – roof top PV at logistics hub

In case of logistics hubs, a combination of charging infrastructure with rooftop PV generation offers potential synergies. Assuming an average 40% share of buildings of the total net area and ratio of PV module area to roof area of about 40%, about 0.16 MW_p of PV capacity[20] can be installed per ha. This installed capacity can po-

---

[20] MW_p refers to the nameplate capacity of the installed PV modules. This capacity is different from plant capacity from a network point of view: the power converters at the interface with the electrical network will never

tentially generate about 150 MWh annually (German average, no significant shadowing or mismatch).

These figures can be compared with the key parameters for the charging infrastructure. A capacity of 0.16 MW_p/ha is clearly lower than the grid connection capacity of 0.5 MW/ha required for charging BE SH and LH trucks. In other words: the grid connection for truck charging in a high penetration scenario is sufficient to connect roof-top PV generation at no extra grid connection costs.

The annual generation represents about 10% of the annual consumption for truck charging modelled here. This low share, together with the low-capacity ratio guarantees that even in summer the complete PV yield is immediately consumed on-site and no export needs to take place.

Case 2 – PV capacity matching grid connection for truck charging

A connection capacity of 0.5 MW/ha allows to connect a PV plant rated at about 0.65 MW_p/ha (German conditions). This figure takes into account that permanent curtailment of PV to about 75% of the nameplate capacity results in economically acceptable annual yield losses of not more than 2% to 3%. Control interfaces for curtailment may be required to satisfy the regulations of the network operator. Reflecting the permanent load for charging trucks, however, curtailment may (almost) never be activated and respective losses may never occur.

The annual yield corresponds to more than one third of the energy charged into truck batteries at the logistics hub. In this case not each and every kWh will be absorbed directly by the chargers, though. At least one of the charging profiles resulting from the estimates in section 3.2.1 is not closely correlated with the daily cycle of solar radiation. At noon, the peak PV generation may exceed the rather moderate load during the sunny months in summer. Hence, a minor share of the generation will be fed into the grid. A

---

export more than their rated capacity, regardless the power offered by the PV plant. Generally, the converter capacity is lower than the installed capacity of the PV modules, simply because this is economical.

quantitative analysis requires modelling and goes beyond the scope of this analysis.

The mentioned PV capacity implies that additional space is available for the generation facility adjacent to the logistics hub. Roughly speaking, each ha net area of the logistics hub requires an additional 0.5 to 1 ha of greenfield PV. In many cases, space limitations will form the relevant restriction for this case.

Case 3 – maximising PV capacity for the grid connection using generation management

As discussed in case 2, physical export of electricity will be quite limited even if the PV capacity matches the rating of the network connection. This is due to the fact, that the expected minimum load at the logistics hub during daytime is always at least 50% of the peak load from truck charging. Export of electricity only starts if this level is going to be exceeded. Depending on the exact charging profiles at a certain logistics hub, the PV capacity may be twice the capacity of the network connection before preventive action has to be considered in order to avoid overloading of assets.

The yield of this option would correspond to 50% to 75% of the energy used for charging the trucks. However, a significant share of this generation would not be absorbed at the site but exported due to the lacking match in time. Business models relying on net metering do not apply to this case.

The PV facilities require space of clearly more than one ha per ha of the logistics hub. For utilisation of the same grid connection the PV area should be adjacent to the location of the hub. From a perspective of spatial planning and efficient utilisation of space, suitable sites will be the exception.

Combination of local energy generation with stationary storage

The cases above illustrate that the share of PV generation immediately used at the site is high for realistic scenarios, even without any electricity storage. Hence, the combination of PV and storage does not offer additional benefits on top of those discussed in paragraph 4.1.

4.3 Local DC Distribution grids

A technical alternative to low voltage AC distribution is the use of a local DC distribution grid. In this case, large, possibly modular rectifiers are connected directly to the supplying MV-LV distribution transformer. The individual chargers are connected to the shared DC bus (see Figure 4-6). The power electronic converters of the chargers are reduced to DC-DC-converters providing charging control (current, voltage).

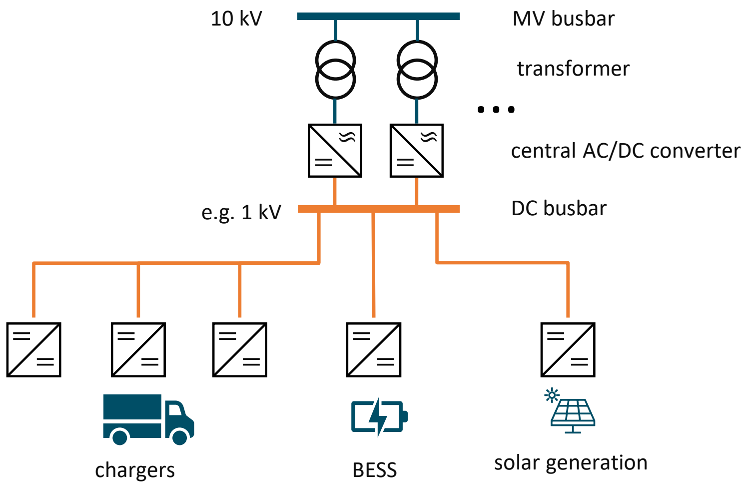


Figure 4-6: DC distribution for charging infrastructure

Within this concept, voltage levels of up to 1 kV are a realistic option[21]. AC losses are avoided and, simultaneously, effective cross section of copper conductors can be reduced. The central rectifier offers some cost reduction potential compared to its equivalent in the individual chargers. Logically, the advantages of the concept materialise if multiple chargers are supplied by a single rectifier. Hence, the benefits are limited in case of a dedicated transformer per MCS as introduced in paragraph 2.4[22]. Specific investments

---

[21] Higher voltages imply the step from low to medium voltage with more challenging component rating and stricter safety guidelines.

[22] In this case it is most economical to place the transformer as close as possible to the charger and restrict low voltage distribution to the absolutely necessary minimum.

can be reduced additionally, if stationary BESS or local solar PV generation are directly connected to the DC busbar.

Compared to existing AC technology, the concept is technically challenging and requires further research and development. For deploying the cost reduction potential, standardisation and economies of scale are crucial. The large number of public NCS required for BE-LH trucks and the combination with chargers for BE passenger vehicles is a promising basis for progress.

5 Findings, conclusions and recommendations

5.1 Findings and conclusions

The three prototypical charging stations analysed in the framework of this study cover a large share of the charging infrastructure required for the future transition to BE-LH trucks.

The prototypical charging stations are technically feasible. The service levels assumed in the study match with the current operational processes of logistics companies.

Active charging management is a crucial factor for the reduction of grid connection costs and can be integrated without negatively affecting the service level of the charging stations. This applies especially to charging stations combining megawatt and overnight charging which promise high synergy effects with respect to grid connection requirements. The integration of battery storage systems is, with regard to the analysed station design, not beneficial and is in competition with the (much cheaper) charging management. However, for pure MCS stations the combination with battery storage systems, that reduce the necessary grid capacity is likely to be technically and economically feasible.

The implications of the prototypical charging stations along the motorway networks (prototype 1 “high traffic volume” and 2 “low traffic volume”) are not associated with fundamental challenges. The charging capacity requires a connection at medium voltage or, in cases of high traffic in the high voltage level beyond 2035. Space requirements at motorway stations will slightly increase. A high predictability of the long-haul truck ramp-up can limit step-by-step reconstruction measures of the grid connection. However, to a large extend the connection concepts are also adjustable without significant additional costs.

In case of logistics hubs (prototype 3), the structure of the area and operational processes will need to be adapted. Dedicated and accessible space for public charging at those hubs, also overnight, will be an essential part of the concept. Currently, those spaces do not generally exist at logistics hubs.

The required capacity of the network connection for the charging infrastructure at logistic hubs is high, in a range between 0.5 MW/ha and 1 MW/ha. This is a factor of 10 to 20 compared to the current situation. Strong HV-distribution networks in the vicinity of logistics hubs will therefore become an important factor for site development.

There may be cases where the considered prototype ratings are insufficient. Examples could be very large logistics areas, very rural regions and, consequently, long distances between charging stations or substations of the electricity network (e.g. Scandinavia). These cases will require further analysis. However, they do not compromise the general feasibility of the concept.

The specific costs of the charging infrastructure are dominated by the cost of the chargers – in most scenarios they represent about 90% of total connection costs. This is even the case if high loads require a separate connection to high-voltage grids. The cost per kWh of the grid connection is, in most cases, not more or below 10% of the total infrastructure-related cost. The level required for refinancing the infrastructure of the prototypes considered in a societal perspective is about 0.05 €/kWh to 0.06 €/kWh. Only in case of prototype 2 (“low traffic volume”) due to lower utilisation rates during the transitional phase (2027 and 2030 scenarios), the specific monetary value of the infrastructure is higher and amounts to between 0.10 €/kWh and 0.14 €/kWh. These numbers do not include cost for electricity supply, taxes, levies, charges or profit margins nor costs for planning, permitting or extra space at the site.

The scenario analysis allows a mutual comparison of the scenario snapshots for the same year. Due to regulated allocation and socialisation of network costs, the results of the analysis are not suitable as a basis for assessing the economic viability of individual projects.

Deploying the existing synergies of on-site PV generation and truck charging at logistics hubs will be challenging due to institutional complexity and the difficulty to synchronise planning and implementation of infrastructure.

5.2 Discussion

The scenario analysis assumed a lean design of the charging infrastructure. An efficient utilisation of the existing assets is crucial. This means that adequate provisions have to be implemented making sure that, for example, the chargers' slots are not occupied after a truck charged the required energy. These provisions may be technical (online booking systems, possibly in combination with robotic solutions for plugging) or organisational (time-related pricing for slots).

The potential implications of parallel, external developments need to be adequately evaluated: With autonomous driving, regulated driving times and rest periods may be abolished altogether and the operational uptime of trucks might possibly increase. Some fundamental assumptions forming the basis of our analysis, such as the daily truck flow patterns, may turn out to be less accurate. This might justify much higher charging powers for public MCS as well as MCS for depot and destination charging.

Making BE-LH trucks a success will require swift attention by policy-makers and regulators. Without reforming the current network regulation, the described developments would quickly face significant regulatory barriers. Merchant investments are associated with high risk and there is no market pull: BE-LH trucks need to be deployed in lock-step with rolling out the necessary charging infrastructure. Designing a supportive and effective regulatory framework, developing suitable policy instruments and enabling viable business models for infrastructure operators will be key.

Due to the long lead times, transmission and distribution grid operators will need to take into account the roll-out of truck charging infrastructure early in their strategic grid planning. Again, a sound and enabling legislative framework will be essential for the timely and coordinated development of the infrastructure.

5.3 Further investigation potential

This study looked at BE-LH trucks and the related charging infrastructure. Future efforts may identify and quantify potential synergies with parallel developments, like charging infrastructure for passenger cars and light-commercial vehicles at the same site.

A better understanding of profiles of truck flows, in particular at logistics hubs, will help to narrow down and consolidate the picture of charging needs and resulting infrastructure requirements. Further efforts may adequately address the various businesses and the diverse character of locations.

The required number of MCS chargers as determined in this study will be subject to sufficient charging opportunities at logistics hubs and depots (i.e. trucks start their daily trip with a full battery). If logistics hubs and depots do not offer sufficient charging opportunities, the respective charging demand will have to be provided exclusively by public charging infrastructure. In this case, public charging stations will need to provide more MCS and NCS. Thus, there is a complex interaction between public charging and other private and semi-public charging opportunities which will require further analysis.

Apart from this interaction, the total numbers of customers per charging station is relatively uncertain. The total growth of long-haul traffic, the share of BE-LH trucks and the “gravitational” effect of pioneer regions cannot be perfectly foreseen. The total customer numbers may thus vary for the exemplary prototypes, while the general range of results holds true for the majority of expectable charging stations. However, more detailed analysis for individual regions could improve the local accuracy of the results.

Also, the behaviour of truck drivers and possible technical developments will influence the future demand for charging infrastructure. We assume that trucks are relocated from an MCS after having received the target charging energy. This behaviour might interfere with the driving time and rest regulations, so that longer standing times could be the result. On the other hand, this challenge could be avoided by use of potential technical solutions such as automatized plugging systems.

The total costs of a European network of charging infrastructure will be – apart from the costs of individual sites – determined by the number of required charging stations. Based on the TEN-T network and observed truck flows together with the results of this analysis, the overall infrastructure demand could be estimated, e.g. by means of spatial optimization methods in future analyses.

Overnight charging offers a high flexibility potential. In this study, we used this potential partially and aimed for a reduction of grid capacity. However, other objectives can be pursued. Possible subjects of further studies are, for example, the provision of ancillary services for the power grid or the integration of (local) renewable power generation.

6 References

[1] European Union (2019). Regulation (EU) 561/2006 of the European Parliament and of the Council., „Retrieved from https://eur-lex.europa.eu/resource.html?uri=cellar:5cf5ebde-d494-40eb-86a7-2131294ccbd9.0005.02/DOC_1&format=PDF,“ [Online].

[2] CharIN e.V., „CharIN HPCCV Task Force - High Power Plug Update,“ see also: https://www.charin.global/technology/mcs/ , April 2020.

[3] Federal Highway Research Institute of Germany (BAst), „Automatische Zählstellen auf Autobahnen und Bundesstraßen,“ 2021. [Online]. Available: https://www.bast.de/BASt_2017/DE/Verkehrstechnik/Fachthemen/v2-verkehrszaehlung/Aktuell/zaehl_aktuell_node.html .

[4] Deutsche GVZ-Gesellschaft mbH, „European Freight Village Ranking 2020,“ Bremen, 2020.

[5] Europlatforms, „Corporate Presentation,“ European Association of Transport & Logistics Centres, 2015.

[6] A. Jordan, „personal communication,“ IPG Infrastruktur- und Projektentwicklungsgesellschaft mbH, Potsdam, 2021.

[7] T. Wagner, „Analysen der Logistikbranche in der Metropolregion Hamburg, ECTL Working Paper 39,“ Technische Universtiät Hamburg-Harburg, European Centre for Transportation and Logistics, Hamburg, 2008.

[8] R. L. G. F. Wulf, „personal communication,“ Großbeeren, January 2021.

[9] T. G. Flako Thomas, „personal communication,“ January 2021, Versmold.

[10] Deutsche Energie-Agentur GmbH (dena), “Ausbau-und Innovationsbedarf der Stromverteilnetze in Deutschland bis 2030,” Berlin, Germany, 2012.

[11] „Stromnetzentgeltverordnung vom 25. Juli 2005 (BGBl. I S. 2225), die zuletzt durch Artikel 1 der Verordnung vom 30. Oktober 2020 (BGBl. I S. 2269) geändert worden ist“.

[12] Nationale Plattform Zukunft der Mobilität, „BEDARFSGERECHTE UND WIRTSCHAFTLICHE ÖFFENTLICHE LADEINFRASTRUKTUR,“ 2021.

[13] Kühnel et al, „Oberleitungs-Lkw im Kontext weiterer Antriebs- und Energieversorgungsoptionen für den Straßengüterfernverkehr. Ein Technologie- und Wirtschaftsvergleich.,“ 2018. [Online]. Available: https://www.oeko.de/fileadmin/oekodoc/StratON-O-Lkw-Technologievergleich-2018.pdf.

[14] DTV-Verkehrsconsult GmbH, „Lkw-Parken auf BAB,“ report on behalf the ministry of transport, construction and urban development, Germany, 2014.

[15] M. Kardolus, „personal communication,“ Power Research Electronics bv, Breda, The Netherlands, 2021.

[16] Fraunhofer Institute for Integrated Systems and Device Technology IISB, „Project HPC-prime in German support programme Elektro-Mobil,“ 2021.

[17] Tsiropoulos,I., Tarvydas,D., Lebedeva,N., Li-ion batteries for mobilityand stationary storage applications –Scenarios for costs and market growth, EUR 29440 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-97254-6, „ doi:10.2760/87175, JRC113360“.

[18] N. R. E. Laboratory, „Cost Projections for Utility-Scale Battery Storage,“ U.S. Department of Energy, 2019.

[19] Westnetz GmbH, „Entgelte für Netznutzung,“ [Online]. Available: https://iam.westnetz.de/ueber-westnetz/unser-

netz/netzentgelte-strom.

[20] Kraftfahrt-Bundesamt, „Kraftfahrzeugverkehr in Deutschland 2010 (KiD 2010),“ final report, Braunschweig, Germany, 2012.

[21] Institut Verkehr und Raum der Fachhochschule Erfurt, „Belegung der Autobahnparkplätze durch LKW in Thüringen,“ study on behalf of the state office for road construction of Thuringia, Erfurt, Germany, 2008.

[22] Fraunhofer-Institut für System- und Innovationsforschung ISI, „Hochleistungsschnellladenetz für Elektro-Lkw,“ study on behalf of the “Verband der Automobilindustrie e.V.”, Karlsruhe, Germany, 2020.

[23] ACEA, Transport & Environment, „Making AFID fit for zero-emission heavy-duty vehicles, open letter to Frans Timmermans,“ April 2021. [Online]. Available: https://acea.be/uploads/press_releases_files/ACEA_TE_letter-Making_AFID_fit_for_zero-emission_heavy-duty_vehicles.pdf.

[24] Transport & Environment, „Unlocking electric trucking in the EU: recharging along highways,“ Unlocking electric trucking in the EU: recharging along highways, Brussels, 2021.

[25] TU Graz, TÜV Nord, icct, TNO, „VECTO tool development: Completion of methodology to simulate Heavy Duty Vehicles' fuel consumption and CO2 emissions,“ *Study on behalf of the European Comission,* 2017.

7 Appendices

7.1 How do we translate investments into annual costs?

In our scenarios, we look at the investments required to satisfy a certain need. The needs grow over time and so do the investments.

We considered three target years and their needs at this particular moment in time. Looking at the modelling results, the step from the 2030s needs to those in the 2040s is substantial. It is obvious that, over that period, further incremental investments are necessary. In our analysis they are virtually projected at 2040 (see Figure 7-1).

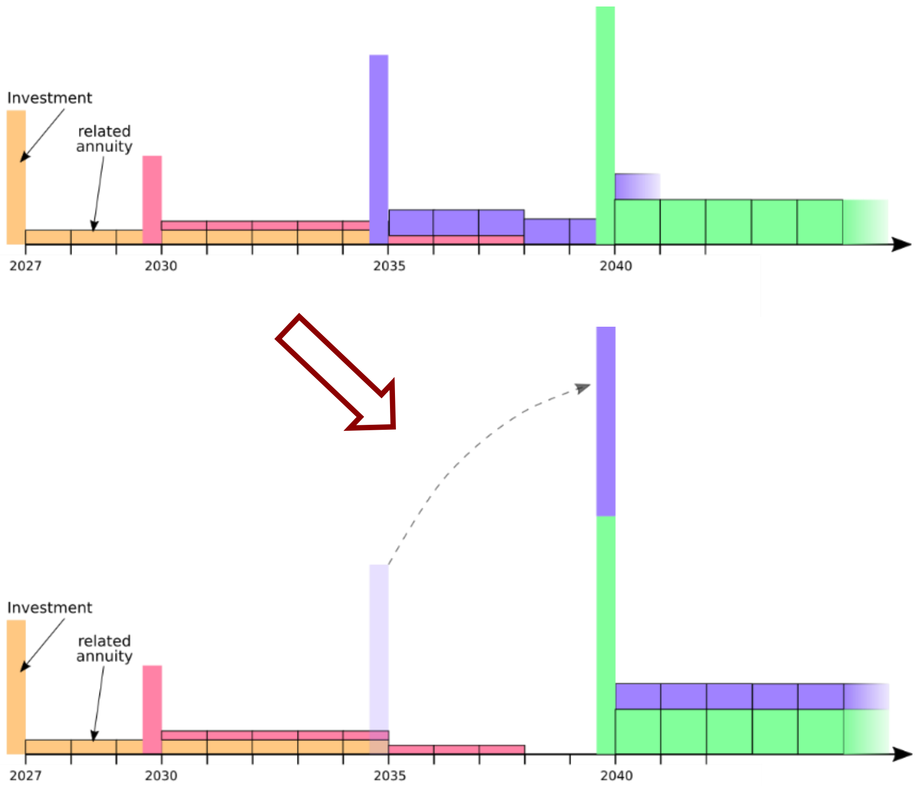


Figure 7-1: Investments between scenario snapshots (e.g. 2035) are virtually projected at the next snapshot (2040)

Additionally, for the chargers we assume a lifetime period being shorter than the scenario horizon. In other words: the chargers need to be replaced somewhere in the period between the target years. This is associated with re-investment which is invisible to the demand associated with the snapshots.

In the report, we focus on annual depreciation rather than investment. The investments related to network assets are depreciated linearly over long periods which would exceed the scenario horizon. We can consider the annual depreciation being constant and add them up for each of the scenario snapshots. We assume that the chargers are replaced at the end of their life with exactly the same investments. Hence, the related depreciation remains the same too.

With the sequence of investments, the cumulative level of annuities increases over time (see Figure 7-2:). For an evaluation of the financial performance of the infrastructure investments along the timeline we relate the annual payments to the service provided for each scenario snapshot (annual number of charging actions, kWh-delivered).

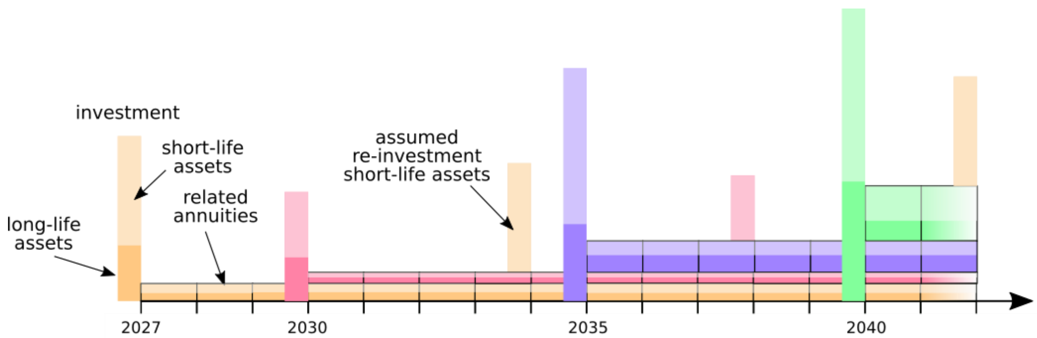


Figure 7-2: All investments (vertical bars) are translated in depreciation (block per year). Assets with a short life (chargers, light colour) are assumed to be replaced against identical cost. Hence, depreciation remains constant over the complete scenario period

In some cases, the growth of the BE-LH truck fleet means that a network connection needs to be replaced by a more powerful one long before the original assets are depreciated. This applies, for instance, to the step from scenario 1 to 3 and from 3 to 5. In these cases, the depreciation period is reduced to the real utilisation period of the assets according to the scenario horizon.

We calculate per-asset annuities reflecting realistic expectations on the profitability of the investment[23].

$$AnnCost = \sum_{i}^{n} \frac{Inv_i \times rate}{1-(1+rate)^{-LifeEcon_i}} + OPEX$$

With:

- AnnCost: annual costs associated with the infrastructure in € per year
- i, n: denominator of asset over all n assets covered by a scenario variant
- Invi: investment related to asset i in €
- LifeEconi: economic life of asset i in years
- Rate: interest rate for evaluation of investment
- OPEX: annual operational costs in € per year

For each group of assets according to Table 2-3 we use utilisation periods in line with the German regulation [11]. We do not differentiate between interest for equity and external capital. For all assets we apply a uniform interest of 5%.

[23] Usually, economic life, i.e. the common depreciation period of assets, is shorter than technical life. We ignore this difference in our analysis. Given the long depreciation periods of network assets the impact on the result is negligible.

7.2 Model of truck behaviour

The necessary charging infrastructure for BE-LH trucks depends on the traffic flows and charging behaviour. The number of customers, their distribution throughout the day and the necessary charging energy are of special interest and determine the required number of chargers and the necessary charging power. A concentration of many vehicles within a short time period would, for example, require more chargers compared to an even distribution throughout the day. The energy demand per charging process also affects the demand for charging points. Longer charging times will result in a higher number of chargers required.

Additionally, there is a trade-off between high-power and megawatt charging as well as overnight charging. If high-power charging is used more frequently, the charging energy of overnight charging can be reduced (and vice versa). We assume that high-power charging will, in practice, be more costly. Consequently, trucks are expected to only recharge at high-power chargers to reach their destination and guaranteeing a safety margin of 20% SoC.

Mobility model for high power charging

The applied modelling framework *e.mission*, which ensures an efficient dimensioning of megawatt charging stations and overnight charging infrastructure, relates to a certain traffic flow of vehicles which arrive at the charging station. This traffic flow represents the driving, resting and charging behaviour of BE-LH trucks in a realistic way.

Figure 7-3 gives a summary of the developed model, which is based on a Monte-Carlo approach. The model generates the behaviour of a random sample of long-haul trucks, arriving at different charging locations (MCS or overnight charging). A subset of this sample is fed into the below described model in order to determine the dimensioning of the charging infrastructure.

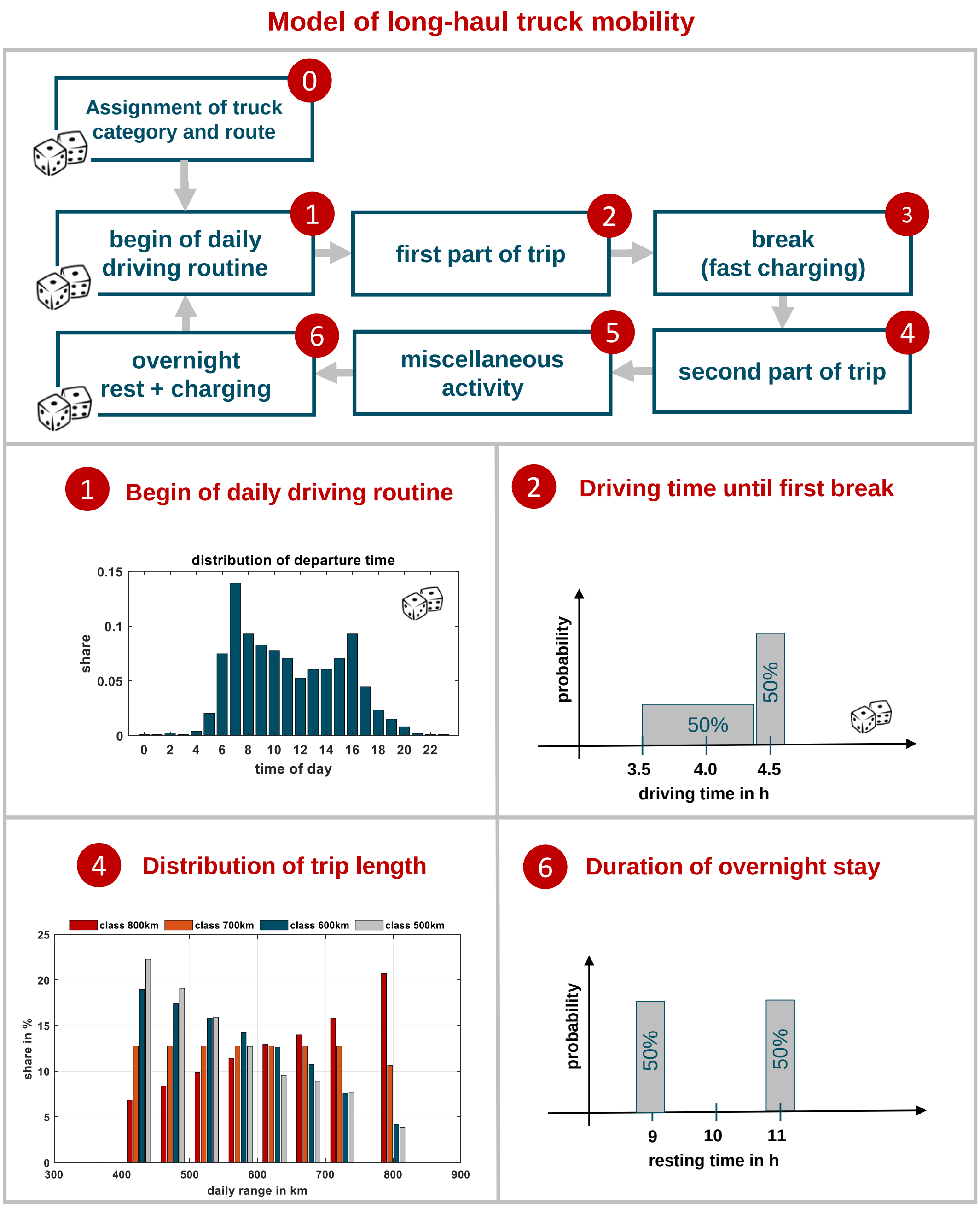


Figure 7-3: **Model of long-haul truck mobility**

In the first place (0), a truck is assigned to one out of four types of trucks (see Table 7-1). According to the different operational mission profiles and duty cycles, the long-haul fleet consists of vehicle categories with different ranges and battery capacities.

Table 7-1: Categories of long-haul trucks

category	truck category name	net battery capacity	max. charging power	target SOC HPC	max. range	energy consumption battery-to-wheel	energy consumption plug-to-wheel	weighted share at HPC
#		kWh	kW	%	km	kWh/km	kWh/km	%
1	long-haul (long)	955	1,200	80%	800	1.19	1.26	43.1%
2	long-haul (medium)	835	1,200	80%	700	1.19	1.26	28.9%
3	long-haul (short)	716	750	80%	600	1.19	1.26	18.7%
4	line-haul	597	750	80%	500	1.19	1.26	9.4%

Each category is then assigned to a specific share of the overall fleet of long-haul trucks. Additionally, a random daily trip length is assigned to each randomly generated truck, based on [ISI2020] (resp. on KiD2010]). Since this project focusses on long-haul freight activity, only truck trips above 400 km are considered.

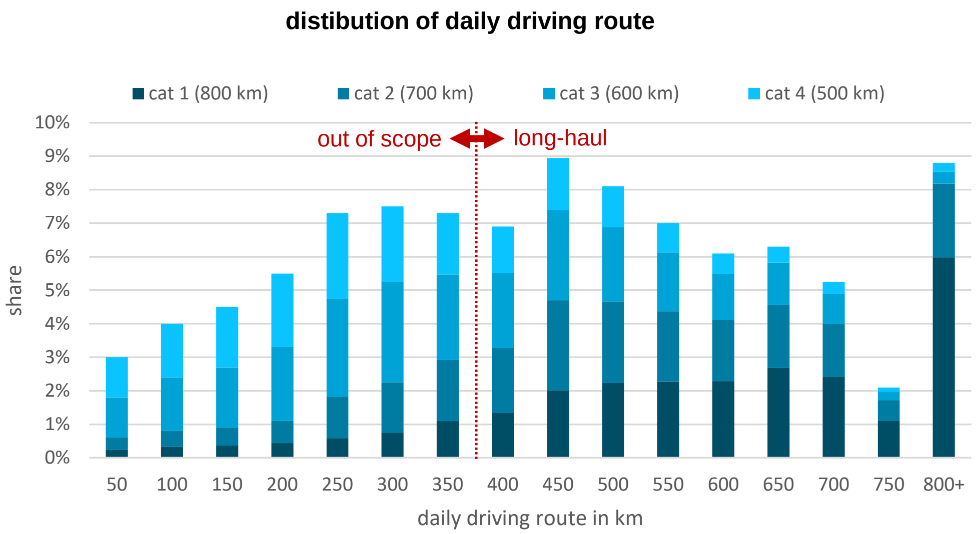


Figure 7-4: Distribution of daily driving range per truck category

The set of possible combinations of the maximum truck range and the daily driving routine imply that not all trucks need to necessarily recharge at a public truck charging station but can be recharged at their home depot or logistics hub (e.g. trucks with a maximum range of 700 km that run 500 km/day). In contrast, trucks with a longer trip length are more likely to stop and charge at a public charging station.

To determine the share of truck categories, which use an MCS station, the fleet share needs to we weighted based on the weighted share of the daily trip among all truck trips (to account for the fact that trucks with longer routes are more likely to stop at a specific charging station). The results of this process are shown in Table 7-1 in the column “weighted share of MCS”, which is used for a random choice of truck category within the Monte-Carlo simulation.

After the determination of the truck category and daily trip length, the beginning of the daily driving routine is randomly determined (1). The applied distribution is obtained from [20], a traffic counting study of the freight flows in Germany (see Figure 7-3).

In a next step (2), the driving duration until the first break is randomly chosen (for the applied distribution, see Figure 7-3). The driving time due to the EU Regulation on driving times and rest periods [1] is limited to 4.5 hours and requires a subsequent break of typically 45 min.

During this break (3), the respective truck is recharged at an MCS station. It can be assumed, that MCS will in practice be more expensive than overnight charging (in terms of costs per kWh). Accordingly, trucks only recharge the amount of energy, which is necessary to fulfil the daily trip length and keeping a safety margin of 20 % SoC at the end of the trip. Additionally, smaller energy requirements below 50 kWh are ignored, and it is assumed that the truck driver will instead opt to slightly reduce the safety margin of 20 % SoC.

After the 45 min break, the truck drives its daily range. Due to the maximum regular driving time of max. 9 to 11 hours, no additional break for high-power charging is necessary. This is due to the fact that after the charging break, a maximum of 5.5 to 7.5 h driving time remains until the truck arrives at the destination. With an average speed of 86 km/h[24], this equals 473 to 645 km and is only exceeded by a negligible fraction of trucks.

---

[24] In practice, the average speed will lower than this value (e.g. in case of traffic jams or construction sites). With this value, we assume a worst-case scenario.

After the second part of the trip, the truck conducts a “miscellaneous activity” (5), which results from the remaining time of day, after all other activities are performed (sum of overnight resting, driving and breaks). Subsequently, the truck driver performs the mandatory daily rest period. According to the EU regulation, we assume 11 hours per day for all trucks. The time of arrival as well as the remaining SOC are explicitly stored for the subsequent analysis of the overnight charging infrastructure.

Arrival times for overnight charging

While the charging behaviour of long-haul trucks is little investigated, statistics of the parking behaviour at overnight parking lots already pre-exist. One example is [21], which involves a manual counting and tracking of trucks at motorway resting areas. Based on these results, we fitted a lognormal distribution to the observed arrival times of trucks with a rest period of more than 8 hours (see Figure 7-5). The right side of the figure shows the occupation of a parking lot with a rest period of 9 or 11 h and a supply quote of one parking lot per daily truck arrival (“1:1”).

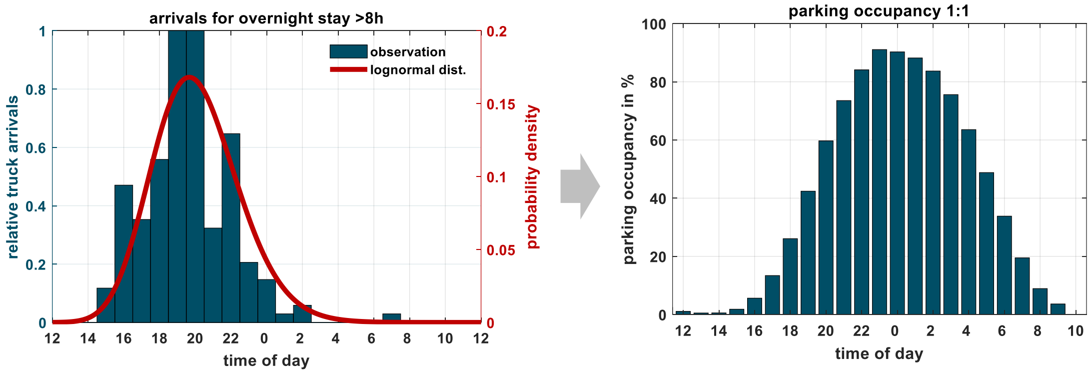


Figure 7-5: Counted and fitted distribution of truck arrivals (left) and the resulting occupation of the parking lot (right) - results for one driving direction

These statistics are generally closer to reality and the arrival times of the previous modelling approach are thus replaced by these figures. Truck categories and charging demands are maintained from the previously described modelling framework *e.mission*.

Mobility modelling results

The above-described model is further used to generate some 100,000 arrivals of vehicles. In a next step, this random sample is fed into the subsequent model for the determination of an optimal charging station configuration.

Additionally, the random sample can be used to identify key features of the behaviour of BE-LH trucks regarding public megawatt and overnight charging. Figure 7-6 shows the key results of the long-haul truck mobility modelling. The left side shows the distribution of arrivals at the HPC in grey and at the overnight chargers in blue. It becomes clear, that the peak for the MCS occurs between 10:00 am and noon, 3.5 to 4.5 hours after the majority of truck departures. For the overnight parking lots, the main arrival time is between 6:00 pm and 10:00 pm. Due to the long standing time, the maximum occupancy occurs between 10:00 pm and 2:00 am.

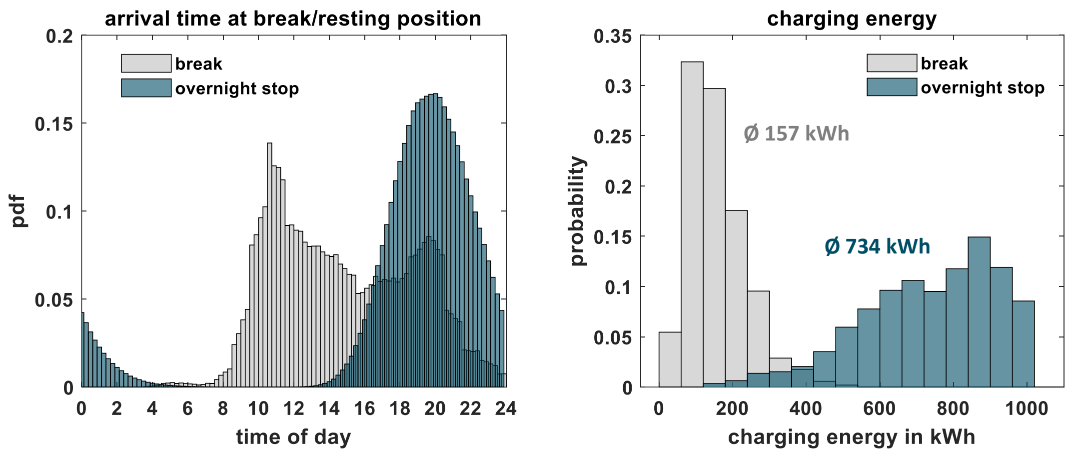


Figure 7-6: Distributions of arrival times and charging energy

The right side of the figure shows the distribution of charging energy per charging session. It becomes evident that the demand for MCS energy with an average of 160 kWh is much lower than the average overnight charging demand of 730 kWh.

7.3 Dimensioning of MCS infrastructure

Customer volume at MCS stations

The previously introduced model explains the structure of the charging behaviour but does not calculate the total volume of customers at a specific location of an MCS station. This needs to be determined in an additional step.

For the prototypes I and II, which represent public MCS stations along the motorways, the analysis draws from the total traffic flows on today's motorway network. In Germany, this traffic volume is tracked by an automatic counting station network, whose data is publicly available [3]. A growth rate of the total long-haul traffic is thus not regarded and remains on the numbers of 2018 (according to the approach in [22]).

Based on the average of counted tractor trailers[25] per day in 2018, the prototypes I and II are allocated to illustrative locations along the German motorway network. According to the prototype objective, prototype I represents the peak demand, while prototype II represents the lower bound of feasible locations for truck megawatt charging (see Figure 2-2).

The daily sum of trucks is further used to simulate the customer outcome of the MCS stations. However, in the applied scenarios, only a certain share of trucks is battery electric based on the fleet penetration rates in a given year. Additionally, the density of the charging infrastructure plays a major role for the customer volume of individual stations.

To estimate the daily customer volume $C_{HPC}(d)$ for each scenario, we assume that:

$$C_{HPC}(d) = C_{semi}(d) \cdot r_{BET} \cdot r_{density} \cdot r_{HPC} \tag{7-1}$$

where $C_{semi}(d)$ is the daily count of a tractor trailer at the corresponding counting station, r_{BET} the share of battery electric trucks among the long-haul truck fleet and r_{HPC} the share of long-haul trucks, whose trip length exceed the maximum range. Further, $r_{density}$ is the ratio of the MCS station density and 387 km, the distance a truck can go within the maximum driving time of 4.5 h

[25] We use numbers for tractor trailers only, in order to focus on long-haul traffic only. According to [25] (p. 117), 70% of the tractor trailers are used for long-haul traffic, while 27 % of the long-haul traffic is using rigid trucks instead of tractor trailers. As a simplification, we counted all tractors trailers as long-haul traffic and in return neglected the share of long-haul journeys in the rigid truck traffic.

with a speed of 86 km/h. The latter factor accounts for the fact that the customer volume is distributed among competing charging stations and is thus lower if the density of charging stations is higher.

Figure 7-7 shows an exemplary result of this approach for scenario 4 and the driving direction west. Peak customer volumes occur in the weeks before the Easter and the Christmas holidays, which are essential for the subsequent analysis of the charging infrastructure.

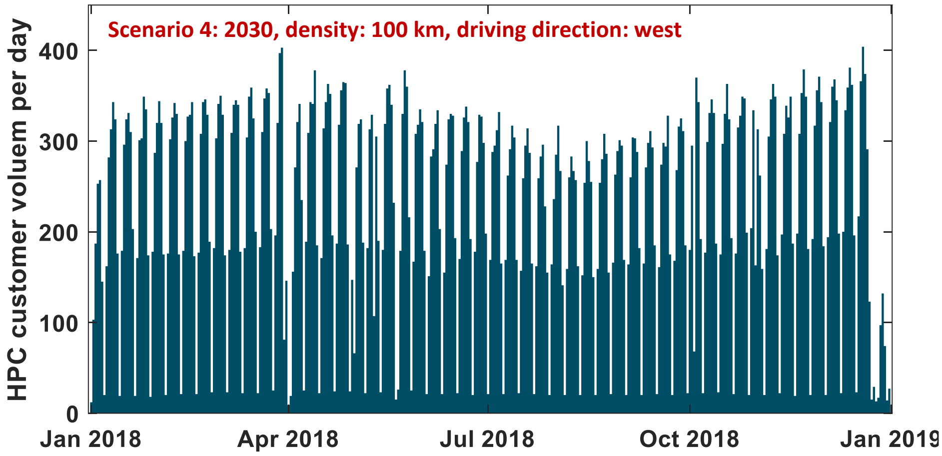


Figure 7-7: Daily MCS customer volume for scenario 4 (one direction)

Table 7-2 gives an overview over the results for all regarded scenarios of prototype I and II.

Table 7-2: Calculation of customer volumes (one direction)

Prototype	Scenario No.	Year	Station density in km	Share long-haul	Share BET	Factor Density	Factor MCS necessary	Resulting Share	max. trucks per day (all types)	max. trucks per day (MCS)
Prototype I	1	2027	100	100%	7.5%	27.8%	55.0%	1.15%	13193	151
	2		200	100%	7.5%	55.6%	55.0%	2.29%	13193	302
	3	2030	50	100%	20.0%	13.9%	55.0%	1.53%	13193	202
	4		100	100%	20.0%	27.8%	55.0%	3.06%	13193	403
	5	2035	50	100%	50.0%	13.9%	55.0%	3.82%	13193	504
	6	2040	50	100%	80.0%	13.9%	55.0%	6.11%	13193	806
Prototype II	7	2027	100	100%	2.6%	27.8%	55.0%	0.40%	2951	12
	8		200	100%	2.6%	55.6%	55.0%	0.80%	2951	24
	9	2030	50	100%	7.0%	13.9%	55.0%	0.53%	2951	16
	10		100	100%	7.0%	27.8%	55.0%	1.07%	2951	32
	11	2040	50	100%	60.0%	13.9%	55.0%	4.58%	2951	135

e.mission – E-Mobility Infrastructure Simulation and Dimensioning

The derived customer volumes are subsequently fed into a pre-existing modelling framework *e.mission*. This toolbox determines the optimal dimensioning of the charging infrastructure. It combines a stochastic queueing model with a charging and battery management model (see Figure 7-8). It simulates customer behaviour, charging processes and energy management. The simulation of the charging stations is performed for one year of operation and in a temporal resolution of 5 min. By variation of the available charging and grid infrastructure, as well as potential on-site renewable generation or battery storage systems, an optimal configuration of the charging station is determined.

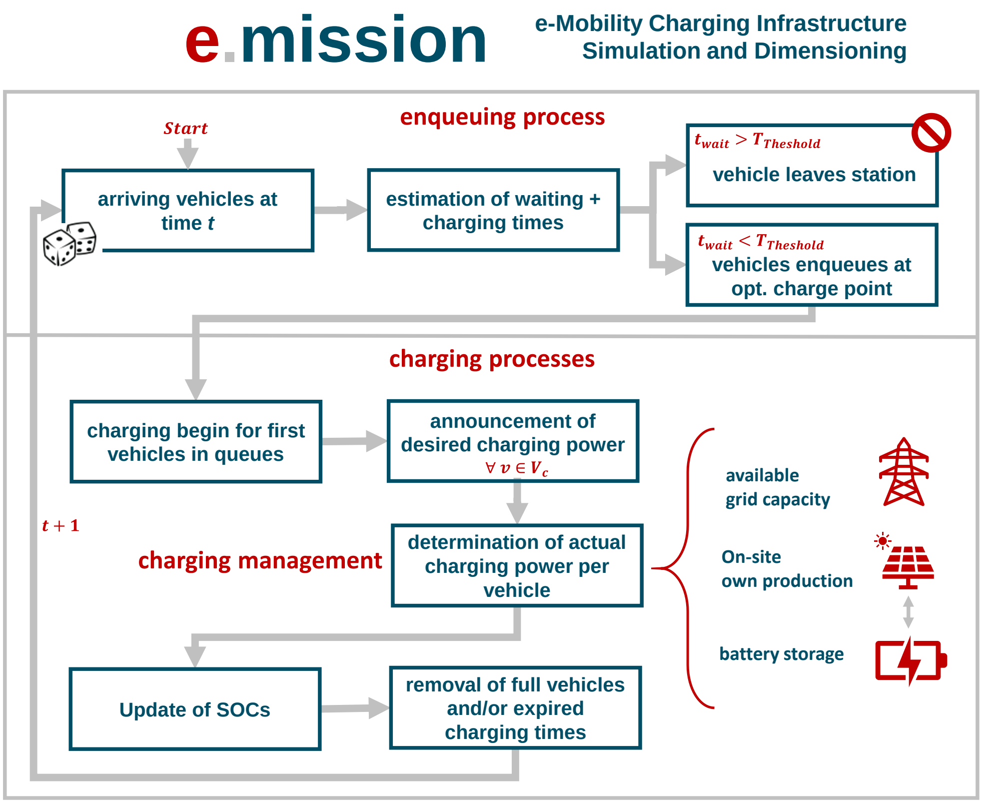


Figure 7-8: Overview of the modelling framework e.mission

Optimal Dimensioning of Megawatt charging infrastructure

In a first step, the pre-existing model of e-Mobility Charging stations is adapted to the special requirements for truck charging.

This involves customer volumes and behaviour, charging power, the SoC-dependent charging behaviour and acceptable waiting times. It is assumed that trucks have no other option than using the regarded charging station and thus tolerate any waiting time at the charging station. However, waiting times (before the beginning of the charging event) higher than 15 min is regarded as inadequate and thus counted as a customer not served"[26].

In addition, we assume the following charging behaviour:

- at MCS stations, trucks charge until reaching 80% SoC and thus with fully rated charging power,
- at NCS trucks charge until 100%.

By variation of the number of MCS charging points, the minimal required number of chargers is determined that still meets customer requirements. Figure 7-9 shows an exemplary interim result of this process for scenario 4. The optimal number of chargers is given by the lowest number of chargers that exceeds a customer satisfaction of 99 %. Thus, inadequate waiting times only occur at the annual rush time before the Easter and Christmas holidays.

[26] If trucks with a waiting time are simply removed from the queue, this would imply that truck drivers have other options than charging at the regarded charging station. Since this is not the case, we must allow longer waiting times in the simulation. Thus, trucks, that had to wait more than 15min before the beginning of charging are considered as unserved customers. This allows for a more realistic judgement of the performance of the charging station.

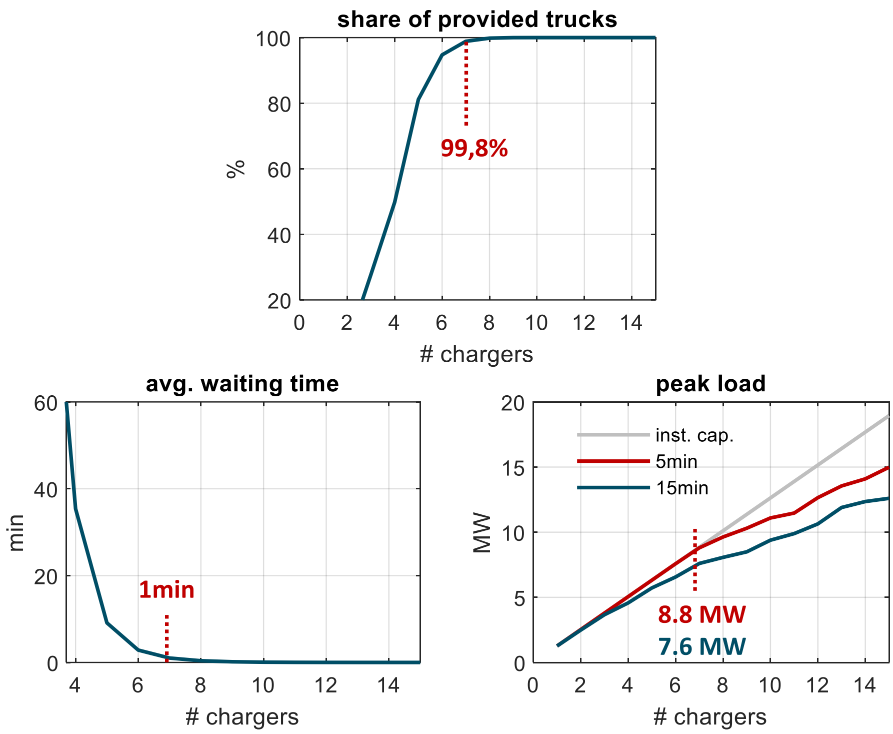


Figure 7-9: Exemplary results for scenario 4 (prototype I, 2030, density 100 km) for different numbers of megawatt chargers and one driving direction

The progression of the peak loads shows that, unlike for high numbers of AC-chargers in a domestic environment, there is no significant declining concurrency for charging stations below 10 MCS. Accordingly, it is assumed that the grid connection power of the MCS part of the charging station equals the installed power of the chargers. A charging management among the MCS is thus not assessed (and generally questionable for this use-case). However, a charging management between the MCS and the overnight charging is applied and laid out in in the following sections.

7.4 Dimensioning of overnight charging infrastructure

According to the EU Regulation (EC) No 561/2006 [1], daily rest periods of 9 to 11 hours are mandatory for drivers. During these rests, long-haul trucks can be recharged with comparatively low power, reducing the necessary quantity of MCS significantly. For the prototype I and II, we assume that overnight parking lots are as today only used by trucks that need to fulfil the mandatory break times (we thus do not assume a migration of trucks to motorway charging stations with the only purpose of using public charging infrastructure).

The necessary number of overnight chargers N_o is determined by the following calculation:

$$N_o = \rho_{parking} \cdot d_{CS} \cdot r_{BET} \quad (7\text{-}2)$$

Here $\rho_{parking}$ denotes the line density of parking lots for trucks along the regarded motorway, d_{CS} the assumed distance between long-haul charging stations and r_{BET} the fleet share of BE-LH trucks.

For the regarded motorways (A2 and A31) $\rho_{parking}$ is determined by a manual counting exercise along the motorway network, based on satellite images. For the prototype I (A2 between Berlin and Hanover) 542 parking lots per 100 km and driving direction were identified (prototype II: 143). Table 7-3 shows the resulting number of overnight chargers.

Table 7-3: Required number of overnight chargers (one driving direction)

Prototype	Scenario #	Year	parking density #/100km	charging station distance km	Share BET	number of overnight chargers #
Prototype I	1	2027	542	100	7.5%	41
	2		542	200	7.5%	81
	3	2030	542	50	20.0%	54
	4		542	100	20.0%	108
	5	2035	542	50	50.0%	136
	6	2040	542	50	80.0%	217
Prototype II	7	2027	143	100	2.6%	4
	8		143	200	2.6%	8
	9	2030	143	50	7.0%	5
	10		143	100	7.0%	10
	11	2040	143	50	60.0%	43

7.5 Charging Management

Unlike for megawatt charging, overnight chargers are assumed to be connected during a truck's whole rest period. Additionally, the actual charging time is, due to the combinations of the trucks' battery capacity and daily trip length, significantly shorter than the actual rest period. This results in a high potential for charging management for overnight chargers. Figure 7-10 demonstrates this effect: The maximum charging time of all overnight charging processes is less than 5.5 hours, leaving at minimum 3.5 hours for charging management. The distinct peaks result from the four truck range categories and the assumed safety margin of 20 % SoC (the target SoC for the determination of the necessary MCS energy).

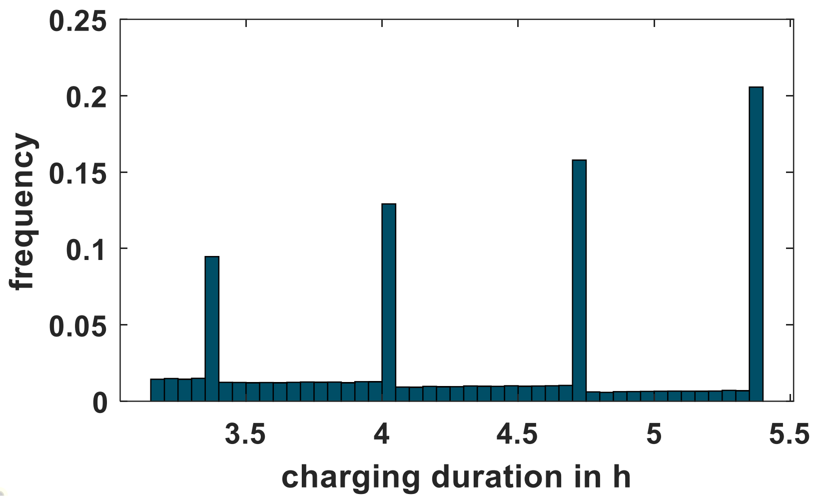


Figure 7-10: Distribution of charging duration of overnight charging processes at 150 kW charging power

Since the minimum grid capacity of the truck charging stations is already set by the installed power of the megawatt chargers, it is desirable that the combined charging power for MCS and overnight charging does not exceed this value. Accordingly, the previously introduced model for the dimensioning of charging stations is applied, including charging management.

The assumed charging management aligns the total power of the overnight chargers with the installed capacity of MCS, reduced by the simultaneous power demand of the MCS chargers. Figure 7-11 shows the charging power for two exemplary days (left) and the average charging profile of weekdays (right).

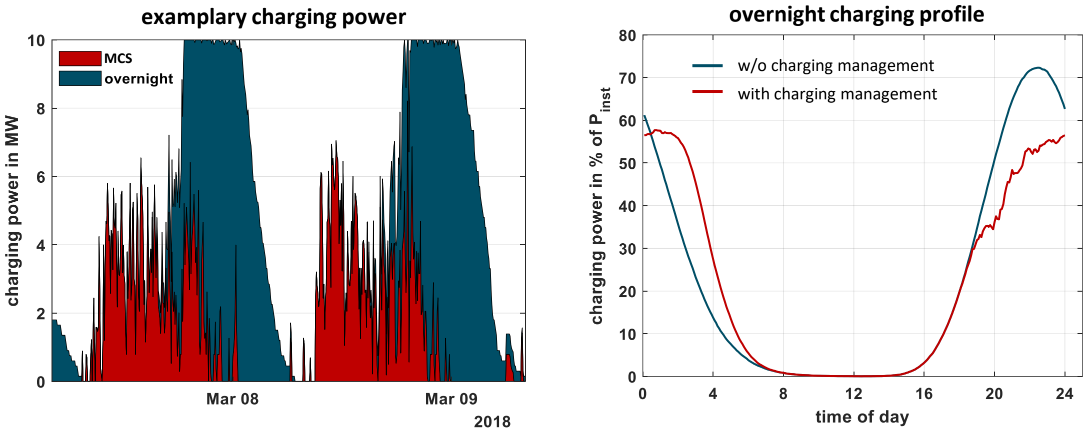


Figure 7-11: Overnight charging management (scenario 5, one driving direction)

According to this concept, the total power of MCS and overnight charging cannot exceed the installed grid capacity. An exaggeration of this concept would thus result in truck with a partially empty battery after the overnight stay.

Nevertheless, in all scenarios analysed (1, 2, 4 and 10) all overnight charging processes were always 100% completed. This indicates a high certainty that these will be the case for the other scenarios as well. Nonetheless, it cannot be excluded that there might be scenarios where this is not achieved.

Consequently, the grid connection of the charging station has to account for the installed capacity of the HPC chargers only, while the additional capacity of the overnight chargers can be shifted through charging management.

7.6 Modelling results overview

Prototype	Scenar-io #	Year	Station density km	Share BE-LH %	peak power MCS (1 dir.) MW	over-night chargers (1 dir.) #	peak NCS (1 dir.) MW	sum of peak powers MW	grid capacity incl. charging management (1 direction) MVA	consumed energy MCS (1 dir.)) GWh	consumed energy NCS (1 dir.) GWh	consumed energy total (1 dir.) GWh	full load hours h	max. queue length MCS #
Prototype 1 "high traffic volume"	1	2027	100	7.5	3.8	41	6.8	10.6	3.8	3.8	9.1	13.0	3,409	11
	2		200	7.5	6.3	81	13.4	19.7	6.3	7.6	18.0	25.6	4,059	23
	3	2030	50	20	5.1	54	8.9	14.0	5.1	5.1	12.0	17.1	3,386	14
	4		100	20	8.8	108	17.8	26.7	9.0	10.2	24.0	34.2	3,802	27
	5	2035	50	50	10.1	136	22.4	32.5	10.1	12.7	30.2	42.9	4,250	31
	6	2040	50	80	16.4	217	35.8	52.2	16.4	20.3	48.7	69.0	4,208	31
Prototype 2 "low traffic volume"	7	2027	100	2.6	1.3	4	0.66	1.9	1.3	0.27	0.88	1.16	916	2
	8		200	2.6	2.5	8	1.32	3.8	2.5	0.54	1.77	2.31	915	2
	9	2030	50	7.0	2.5	5	0.82	3.4	2.5	0.36	1.11	1.46	579	2
	10		100	7.0	2.5	10	1.65	4.2	2.5	0.73	2.21	2.94	1,164	3
	11	2040	50	60.0	3.8	43	7.09	10.9	3.8	3.11	9.50	12.61	3,328	8