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Future Demand and Costs of Megawatt Charging for Battery Electric Trucks

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Abstract

Greenhouse gas emissions from heavy-duty vehicles (HDVs) must be drastically reduced. Battery electric trucks (BETs) are the main option for low-carbon road freight transport, but they require recharging infrastructure. However, a thorough cost analysis of public charging is lacking, especially for the Megawatt Charging System (MCS). This study estimates the infrastructure-related levelised cost of megawatt charging for battery electric trucks in Europe based on simulated truck operations and techno-economic modelling. The analysis combines empirical driving data with cost assumptions for MCS infrastructure. The reported values are infrastructure-only costs and include annualised capital expenditure, installation costs, grid connection costs and operating expenditure. They exclude electricity prices, taxes, levies, land costs and operator margins. Low- and high-cost scenarios differ in assumed charger hardware and installation costs, while grid connection costs and utilisation assumptions are held constant across scenarios. The results show that utilisation is the key driver of cost reductions over time. The infrastructure-related levelised cost of MCS declines to 0.03–0.07 EUR/kWh by 2050 under the analysed cost assumptions. The total annual infrastructure costs for Europe are estimated at 6.6–10.8 billion EUR, or 2.9–4.7 EUR cents/km. The results support policy decisions on infrastructure deployment and highlight the importance of coordinated rollout and demand growth.

Keywords: battery electric trucks; megawatt charging system; charging infrastructure; levelised cost of charging; infrastructure utilisation

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1. Introduction

1.1. Motivation

Heavy-duty vehicles (HDVs) are responsible for a large share of greenhouse gas emissions from road transport. In the European Union (EU), heavy-duty trucks and buses (>3.5 t GVW) account for 7% of greenhouse gas emissions [1]. Battery electric trucks (BETs) are currently considered the most promising option for zero-emission HDVs [2,3]. However, they require dedicated fast-charging infrastructure. The Megawatt Charging System (MCS) standard, currently under development, would enable BETs to operate over long distances by charging at more than 500 kW during regulated breaks. MCS charging would thus complement the expected depot charging [4].

1.2. Existing Literature

The international standard for the technical specification of the Megawatt Charging System is currently under development and expected to be finalised by 2025. For interim truck charging, approximately 400 kWh must be charged within 30 to 45 min, requiring an average power of 750 kW or a peak power of up to 1.5 MW [4]. The MCS standard is planned to cover up to 3.75 MW peak power (3000 A, 1250 V) [5]. However, simulations with different charging strategies show that a maximum power of 2.8 MW per charging point will probably be sufficient for trucks, even in demanding scenarios [6].

Megawatt charging infrastructure will require extensive electricity grid connection, making energy management and potentially buffer batteries necessary. Typically, charging locations will be connected to the medium-voltage grid (10–30 kV) with a corresponding transformer. One charging location with several charging points will be a local low-voltage grid (0.4 kV). Each charging point will contain an AC/DC converter to supply direct current to the vehicles via an actively cooled cable. As most charging processes are unlikely to require megawatt charging [4], megawatt charging could be combined with charging infrastructure for lower charging capacities, e.g., 100–350 kW, at one location.

The expected price per kWh paid for charging a truck is the sum of several components. These include electricity costs (energy and power price from the grid operator), the initial grid connection cost of the charging stations (CAPEX), charger costs (CAPEX and OPEX), taxes, levies and a profit margin for the charge point operator (CPO). Additional real-world costs that are often not included in charging-station cost assessments may include land purchase, roof construction and other site-specific costs. In the existing literature, vehicle costs have received considerable attention—for example, as the total cost of ownership (TCO) for vehicles [7], whereas infrastructure costs have received limited attention so far [8]. For BETs, several studies have calculated the required number of public fast chargers and fast-charging stations—for example, Shoman et al. [9] and Speth et al. [10] for Europe and Speth et al. [11] and Hurtado-Beltran et al. [12] for the USA. Other studies have focused on optimal locations [13,14] and station sizing [15]. However, none of them analysed the total costs of charging infrastructure for BETs.

To avoid ambiguity, four cost terms are used consistently in this study. *MCS infrastructure costs* denote the capital and operating costs of MCS charging infrastructure, including charger hardware, installation, grid connection and OPEX. *Infrastructure-related LCOC* denotes these annualised infrastructure costs divided by the annual energy delivered and is expressed in EUR/kWh. *Charging costs* is used only as a broader term where the context includes several cost components. *End-user charging price* denotes the final price paid by vehicle operators and may additionally include electricity procurement, taxes, levies, land costs and operator margins. Unless stated otherwise, all cost results in this study refer to infrastructure-related LCOC or annual MCS infrastructure costs, not final end-user charging prices.

The increasing relevance of battery electric trucks (BETs) and depot-based charging has led to a growing body of literature covering infrastructure requirements, fleet operations and charging strategies. Several of these findings are synthesised in best-practice guidelines for depot charging—for example, by governmental agencies such as NOW [16], highlighting the operational importance of coordinated charging and infrastructure planning. Recent simulation-based studies underline the dominant role of depot charging. Speth and Plötz [4] show that low-power depot charging is sufficient for most truck operations in Germany, enabling electrification rates of up to 90%. Their analysis, based on around 2400 empirical truck driving profiles, further derives aggregated load curves differentiated by charging location and power level. The results indicate a concentration of charging in overnight periods, reflecting typical departure times in early morning hours. An extension by Speth and Paasch [17] demonstrates that optimised charging strategies can substantially reduce peak loads by 50–60%. However, both studies rely on a historical dataset from 2009/10 [18] and do not allow for site-specific infrastructure assessment.

Several case-study-based analyses focus on grid impacts and operational strategies at the depot level. Borlaug et al. [19] estimate depot charging load profiles from real-world operating schedules and show that charging strategies strongly influence load timing. Similar findings are reported by Garrido et al. [20], who analyse drayage truck operations and show that operational constraints and charging control affect tour completion and charging costs. Synthetic depot modelling approaches further highlight the influence of the fleet composition and charging strategy. Walz and Rudion [21] analyse different logistics centres and show that energy demand, peak load and temporal behaviour vary strongly by logistics centre type. Similarly, Bruchon et al. [22] derive national depot-based vehicle data and normalised charging load profiles for medium- and heavy-duty vehicles, showing characteristic temporal patterns across vehicle categories.

Finally, application-specific studies emphasise the importance of real-world operational variability. Link and Plötz [23] show for urban and regional delivery logistics that depot-based charging can enable full electrification in many cases but that extreme operating days significantly affect battery sizing and feasibility. Zackrisson et al. [24] further demonstrate that adapting tour planning to electric operation can improve both electrification potential and economic performance. However, these studies typically do not provide detailed load curves or system-level infrastructure implications.

Taken together, the literature shows that depot charging is the dominant charging strategy for BETs, that charging strategies strongly affect grid impacts and that both empirical driving data and operational assumptions are critical for assessing infrastructure requirements.

Despite the growing literature on charging infrastructure for electric trucks, consistent assessments of system-level infrastructure costs for megawatt charging systems are still lacking. This study addresses this gap by developing an explicit techno-economic cost model. The novelty of the paper is not the review of charging strategies itself but the combination of temporally resolved truck charging demand with an explicit infrastructure cost and utilisation model for MCS deployment. This makes it possible to quantify infrastructure-related LCOC and annual MCS infrastructure costs over time, rather than only estimating technical charging demand or charging locations.

The study differs from earlier work in several ways. First, previous work mainly assessed the technical feasibility of depot charging, public fast-charging demand or charging infrastructure locations. Second, the present study focuses specifically on MCS infrastructure economics and derives infrastructure-related LCOC from utilisation and annualised cost assumptions. Third, it separates charger hardware, installation, grid connection, OPEX and utilisation effects, thereby identifying which components drive the long-term cost development of public megawatt charging. The original contribution is therefore a techno-economic assessment of MCS infrastructure costs for battery electric trucks, grounded in empirical truck operation data but extending beyond earlier demand-only analyses.

2. Data and Methods

2.1. Simulating MCS Demand

This study analyses all daily trips from 2400 HDVs in Germany, including the start time, trip purpose, distance, duration and stop duration. Each HDV is simulated as a BET with fixed battery capacity and a minimum required charging power during stops of at least 30 min to complete all daily driving. The data and method are taken from [4] and described below.

The simulation approach builds on the daily operation of heavy-duty vehicles (HDVs) from the German "Kraftfahrzeugverkehr in Deutschland" (KiD) survey and contains detailed one-day driving profiles for more than 2400 trucks (>12 t GVW), including trip start and end times, distances and parking locations. Each vehicle is simulated individually as a battery electric truck (BET), preserving its observed sequence of trips and stops. The simulation is conducted in discrete 5 min time steps, allowing for a temporally resolved representation of driving, parking and charging behaviour throughout the day.

Vehicle operation is modelled based on a set of techno-economic assumptions for future years (2030–2050). These include improvements in battery-electric driving range (from approximately 450 km to 750 km, increasing over time), reductions in specific energy consumption (e.g., from about 1.1 to 1.0 kWh/km for tractor-trailers) and increasing maximum charging power up to 1.5 MW. The simulation determines the minimum required battery size and charging power necessary to fulfil all daily trips rather than assuming fixed values ex ante.

Charging behaviour follows a rule-based approach derived from operational constraints. Vehicles are charged only during stops of sufficient duration (at least 30 min), reflecting practical limitations for charging processes. Charging is triggered when the battery state of charge (SOC) falls below a threshold corresponding to approximately 25% remaining energy or when this level would be reached on the next trip. This threshold corresponds to roughly 75% of the available driving range being used. A "flat charging strategy" is applied, in which vehicles charge with the minimum required power to reach full charge before the next departure while respecting the maximum available charging power. This approach ensures that charging demand is spread over time and avoids unnecessary peaks. Charging is therefore determined endogenously as the lowest power that allows for completing all subsequent trips within the available dwell time. The simulation explicitly incorporates operational constraints from European driving regulations. If vehicles exceed the maximum continuous driving time (4.5 h), additional mandatory breaks are inserted into the driving profiles, which may also serve as potential charging opportunities. For each vehicle and time step, the model tracks the cumulative distance travelled, remaining energy demand and charging activity. At the end of the simulation day, technical feasibility is assessed: a driving profile is considered electrifiable if (i) the required battery capacity does not exceed the assumed maximum available battery size and (ii) the vehicle can be fully recharged between the last and first trip of consecutive days.

The model output includes, for each vehicle, the required battery size, number and timing of charging events, charging power and total energy demand. Aggregating across all vehicles yields fleet-wide charging demand profiles differentiated by time of day, charging location (public vs. private) and charging power level. Within this study, the resulting charging demand profiles are used to derive the required Megawatt Charging System (MCS) infrastructure and associated utilisation levels for cost modelling. Full simulation details and methodology are provided in [4].

2.2. Calculating MCS Infrastructure Costs and Infrastructure-Related LCOC

To ascertain the total energy per year, assumptions regarding the average utilisation of MCS charging pools over a period of many years are required. One complexity arises from different notions of "utilisation" in the literature. Fast charging station utilisation may refer to "time utilisation", i.e., the share of hours per year a vehicle is connected to the chargers, or to "energy utilisation", i.e., the share of energy delivered compared to the energy that could theoretically be delivered if all chargers were operating at full power all the time.

The analysis includes MCS infrastructure costs usually considered when building charging stations [25,26]: one-time investments, such as CAPEX, and annual operating expenditures. The OPEX values comprise two distinct aspects: a fixed component related to technology maintenance and a variable component that incorporates operational costs. To make the technologies comparable, standard economic modelling [27] is applied, and costs are distributed over the infrastructure lifetime of T years with an interest rate i to obtain the total annual infrastructure cost:

$$C_{tot} = \text{CAPEX} * \frac{i * (1+i)^T}{(1+i)^T - 1} + \text{OPEX} \tag{1}$$

In Equation (1), CAPEX refers to the total investment, i.e., capital expenditure, OPEX refers to the annual operating expenditure, i refers to the interest rate and T refers to the technical lifetime of the infrastructure. The fixed one-time CAPEX is translated into annual costs as an annuity using the annuity factor $[(1+i)^T * i]/[(1+i)^T - 1]$.

Equation (2) defines the infrastructure-related levelised cost of charging (infrastructure-related LCOC) as the ratio of total annualised MCS infrastructure costs to total energy delivered. Infrastructure-related LCOC excludes electricity prices, taxes, land purchase and operator margins unless explicitly stated. An interest rate of i = 3.5% is used throughout, with technology-specific lifetimes of 15 years for depot and MCS charging points. This 3.5% value is a financial discount rate used for annualising capital expenditure and must not be confused with charger utilisation. Utilisation enters separately through annual energy delivered. The interest rate affects annualised cost, whereas utilisation affects how these annualised costs are distributed over delivered kilowatt-hours. Thus, infrastructure-related LCOC is defined in Equation (2).

$$LCOC = \frac{C_{tot}}{E_{tot}} \tag{2}$$

The parameter selection followed a three-step procedure. First, relevant cost and utilisation parameters were screened from the available literature on fast-charging infrastructure, grid connection costs, station operation and heavy-duty vehicle charging. Second, the collected values were checked for consistency with the technical design of MCS stations used in this study, including installed charging power, permanently available grid-side power, station size and expected utilisation during market ramp-up. Third, the resulting parameter ranges were translated into internally consistent low- and high-cost scenarios. The low- and high-cost cases therefore represent coherent scenario variants rather than isolated minimum and maximum values for individual parameters.

The year-on-year developments in Table 1 should not be interpreted as precise forecasts. They are scenario assumptions constructed to reflect plausible technological and market development pathways under limited empirical evidence for MCS deployment. Cost reductions are assumed where learning effects, standardisation, larger production volumes and maturing supply chains are expected. Increasing available power and utilisation over time reflect the assumed transition from early demonstration and initial corridor deployment to more mature station operation with higher electric truck adoption. The scenario inputs were calibrated to remain consistent across cost, power and utilisation assumptions so that changes over time describe a plausible system-level development rather than independent parameter shifts.

The key assumptions for MCS charging stations with several charging points are summarised in Table 1. The table outlines key cost and utilisation assumptions for Megawatt Charging Systems (MCS) from 2025 to 2050. The number of chargers initially increases from 4 in 2025 to 8 by 2030 and remains constant thereafter, with each charger offering 1000 kW of charging power. Permanently available power increases from 500 kW in 2025 to 1000 kW by 2040, representing increasing grid-side and station-side capability during market maturation. Hardware and installation costs decline steadily in both the low- and high-cost scenarios. For instance, low-case hardware costs decrease from 336.6 kEUR/MW in 2025 to 199 kEUR/MW by 2050, while high-case values fall from 460 kEUR/MW to 356 kEUR/MW. Installation costs follow a similar downward trend. Grid connection costs are kept constant at 90 kEUR across all years. This value follows the recommendation of the German Federal Grid Agency [28] to use the typical grid-fee power price component for the grid connection fee; a value of 150 EUR/kW is applied, and a maximum simultaneity of 60% in power demand is assumed. Operational expenditures are assumed to be 3% of CAPEX per year. Utilisation improves over time, with energetic utilisation rising from 4% in 2025 to 12% by 2045 and demand utilisation increasing from 16% to 48% over the same period. These values are not financial interest rates but scenario assumptions describing station throughput and the matching of infrastructure capacity with simulated MCS demand.

Table 1. Assumptions for MCS charging stations.

Parameter	Unit	2025	2030	2035	2040	2045	2050
Number of Chargers	-	4	8	8	8	8	8
Power	kW	1000	1000	1000	1000	1000	1000
Permanently available power	kW	500	800	900	1000	1000	1000
Hardware Costs-low	kEUR/MW	336.6	303	273	245	221	199
Hardware Costs-high	kEUR/MW	460	437	415	395	375	356
Installation-low	kEUR/MW	94.5	85.1	76.5	68.9	62.0	55.8
Installation-high	kEUR/MW	114	108	103	98	93	88
Grid Connection	kEUR	90	90	90	90	90	90
OPEX share of CAPEX	-	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
Energetic Utilisation	-	4%	5%	10%	11%	12%	12%
Demand Utilisation	-	16%	20%	40%	44%	48%	48%

The values in Table 1 are scenario assumptions rather than direct forecasts from a single source. They combine evidence from existing studies on high-power charging infrastructure, grid connection costs and station economics with internal modelling assumptions and discussions with market actors. The assumptions are designed to represent plausible development pathways for MCS charging stations between 2025 and 2050 rather than point predictions. Cost parameters decline over time to reflect expected learning effects, standardisation, scale effects and maturing supply chains. Power availability increases over time to reflect gradual improvements in grid connection capacity and station design. The number of chargers per site is kept constant after the initial ramp-up to represent a stylised mature station layout.

Two utilisation indicators are used. Energetic utilisation denotes the ratio of annual energy delivered to the theoretical maximum annual energy output if the installed charging power were used continuously at full power. Demand utilisation denotes the share of the modelled MCS demand that is served by the assumed station configuration. Both utilisation trajectories are derived from the simulated charging demand and scaled consistently with the assumed market ramp-up of battery electric trucks. They increase over time because a larger electric truck fleet and more concentrated charging demand improve station throughput. Consequently, the values in Table 1 should be interpreted as transparent modelling assumptions for a scenario analysis, not as observed utilisation rates.

3. Results

3.1. Future MCS Demand

Figure 1 shows the simulation results for minimum required charging power. All 2400 truck driving profiles were simulated as BETs, and the lowest charging power required during existing breaks of at least 30 min was determined to complete all driving as BETs.

About 10% of trucks were not electrifiable with the assumed range of 400 km and are therefore excluded from the figure.

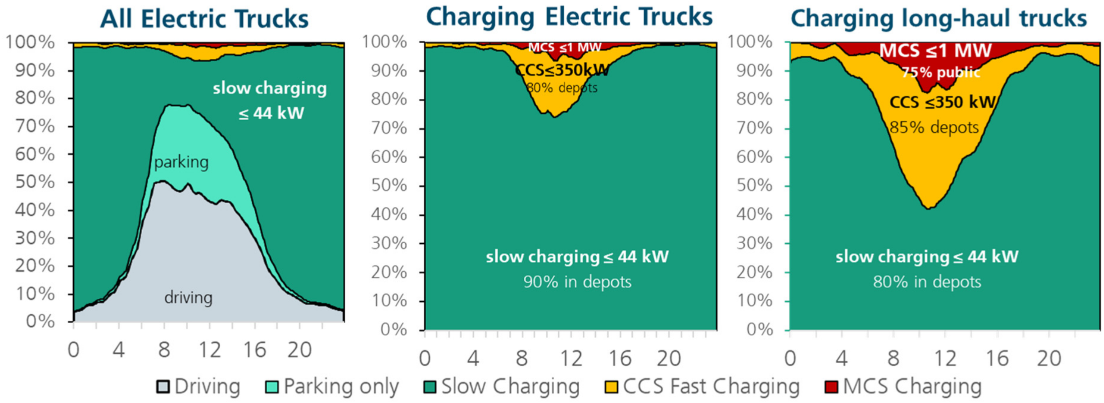

Figure 1. Simulated charging demand and vehicle activity patterns for battery electric trucks based on empirical German heavy-duty vehicle driving profiles. The panels distinguish all electrifiable trucks, trucks that are actively charging and long-haul trucks. Colours indicate the operating state and charging power category, including depot charging, fast charging and megawatt charging. The x-axis shows time of day, and the y-axis shows the share of vehicles. The figure illustrates that most vehicle activity occurs during daytime, while charging opportunities are concentrated during longer stops, particularly overnight at depots and during daytime breaks for long-haul vehicles.

Figure 1 shows that depot charging dominates the charging behaviour of electrifiable trucks. Most vehicle activity is concentrated during daytime, while longer parking periods create substantial opportunities for low-power depot charging outside operating hours. High-power charging, including MCS, is mainly relevant for long-haul trucks and occurs primarily during intermediate breaks. Thus, the figure supports the central modelling result that MCS complements depot charging rather than replacing it. The observed daytime activity pattern is derived from the empirical KiD driving profiles and is not imposed as a fixed working-hour assumption. Individual trucks may operate earlier, later or according to task-specific schedules, but the aggregated data show a concentration of activity between approximately 6:00 and 16:00. This matters for infrastructure planning because it shifts most depot-charging opportunities to evening and overnight periods, while long-haul trucks may require high-power charging during daytime breaks. For trucks that are actively charging, the figure shows that slow charging accounts for most charging events and primarily occurs at depots. Fast charging and MCS represent smaller shares of total charging demand but are important for specific operational cases, especially long-haul operation. This distinction is relevant because infrastructure planning should prioritise depot capacity for most trucks while ensuring sufficient public high-power charging availability for vehicles with long daily distances.

3.2. MCS Infrastructure Costs and Infrastructure-Related LCOC

Figure 2 compares infrastructure-related LCOC for MCS under low- and high-cost assumptions. It does not compare low- and high-utilisation scenarios. The scenarios use the same utilisation trajectory and the same grid connection cost; only charger hardware and installation costs differ. This distinction is important because lower utilisation would increase infrastructure-related LCOC, whereas the lower values in the low-cost scenario result from a smaller annualised infrastructure cost base.

The results show two separate mechanisms. First, higher utilisation reduces infrastructure-related LCOC because fixed annualised MCS infrastructure costs are distributed over more delivered energy. Second, lower charger hardware and installation costs reduce infrastructure-related LCOC because the annualised infrastructure cost base itself is smaller. Figure 2 primarily illustrates the second mechanism by comparing low- and high-cost assumptions, while the common utilisation pathway is embedded in both scenarios. Infrastructure-related LCOC therefore declines over time in both scenarios as station throughput increases and assumed infrastructure costs decrease.

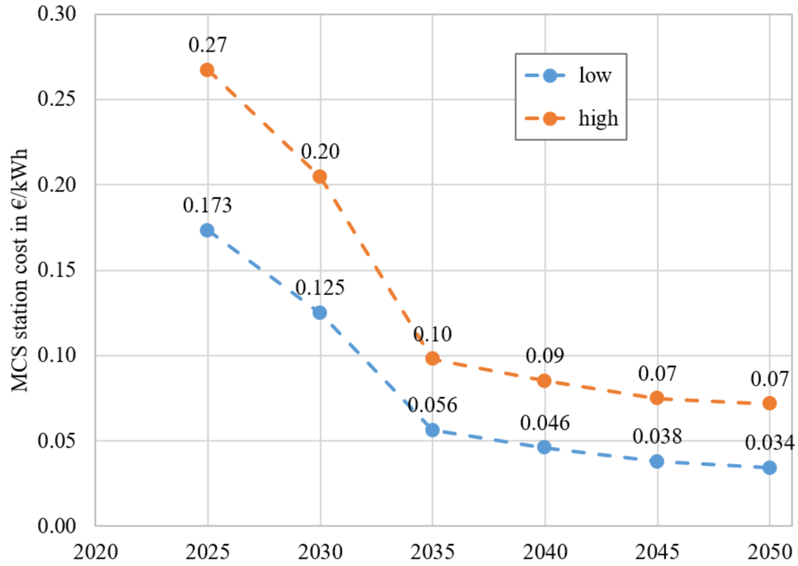

Figure 2. Levelised cost of charging (LCOC) in EUR/kWh for an MCS charging station from 2025 to 2050 under low- and high-cost assumptions. The x-axis shows the projection year. The scenarios differ only in assumed charger hardware and installation costs; grid connection costs and utilisation assumptions are identical across the low- and high-cost cases.

Figure 3 decomposes annual MCS infrastructure costs into annualised CAPEX and OPEX. CAPEX dominates total annual infrastructure costs in all years and scenarios, reflecting the capital-intensive nature of MCS infrastructure. The difference between the low- and high-cost cases is driven by the assumed hardware and installation costs, while grid connection costs are held constant. OPEX remains smaller than CAPEX but becomes relevant for long-term cost recovery because it persists over the full lifetime of the infrastructure.

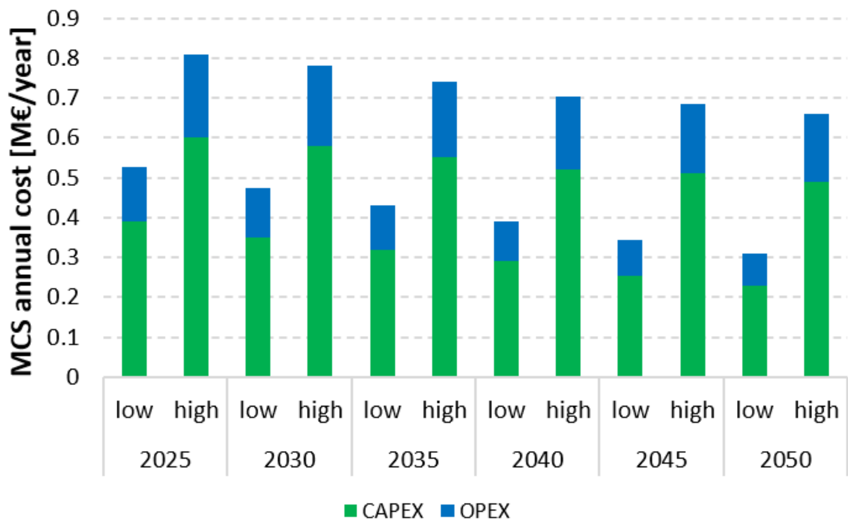

Figure 3. Annual infrastructure costs of an MCS charging station from 2025 to 2050 under low- and high-cost assumptions. Bars distinguish annualised capital expenditure (CAPEX) and annual operating expenditure (OPEX). The x-axis shows the projection year and cost scenario, and the y-axis shows annual station costs in million EUR per year. The figure shows that annual costs are dominated by CAPEX throughout the projection period, while OPEX remains a smaller but persistent cost component.

The main implication is that early MCS deployment is primarily an investment and utilisation challenge. Annual costs remain high while demand is still developing, so low station throughput can translate into high costs per delivered kilowatt-hour even if the technical infrastructure is available. As market uptake increases, the same installed infrastructure can serve more energy demand, improving cost recovery. This reinforces the need for careful station sizing and coordinated rollout rather than simply maximising installed charging capacity.

4. Discussion

This study combines an empirical simulation of truck charging demand with a techno-economic assessment of MCS infrastructure costs. The results show that megawatt charging is mainly relevant for long-haul operation, while most charging demand remains at depots and at lower charging power. The economics of public MCS infrastructure depend strongly on utilisation, especially during early market ramp-up when infrastructure may be deployed ahead of demand. Infrastructure planning for heavy-duty electric vehicles should therefore consider not only technical feasibility but also demand timing, infrastructure scaling and cost recovery.

The findings are consistent with earlier work showing that depot charging is the dominant option for BETs, while public high-power charging mainly serves long-distance use cases. The contribution of the present study is to extend these demand-side findings by quantifying the infrastructure cost consequences of MCS deployment. By linking simulated charging demand to annualised infrastructure costs, utilisation assumptions and infrastructure-related LCOC, the analysis adds an economic layer that was not addressed in earlier demand-focused studies.

A central result is that utilisation drives infrastructure-related LCOC. Because MCS infrastructure has high upfront investment and comparatively low variable costs, underused capacity leads to high costs per delivered kilowatt-hour during early deployment. As charging demand grows and station throughput increases, infrastructure-related LCOC declines substantially. Policies or business models supporting early deployment may therefore be needed to bridge the initial underutilisation phase of public MCS infrastructure.

A sensitivity analysis for the low-cost case further illustrates the magnitude of the utilisation effect. In this sensitivity, the assumed utilisation trajectory from 2025 to 2050 was reduced by 50% in each model year, while all other low-cost assumptions were kept unchanged. The resulting infrastructure-related LCOC increases substantially and in several years exceeds the high-cost case with baseline utilisation. For example, in 2025, the low-cost scenario rises from 0.17 EUR /kWh under baseline utilisation to 0.35 EUR/kWh under half utilisation, compared with 0.27 EUR/kWh in the high-cost case. In 2030, the corresponding values are 0.12 EUR/kWh, 0.25 EUR/kWh and 0.20 EUR/kWh, respectively. Even in later years, the effect remains material: by 2045 and 2050, the half-utilisation case reaches 0.08 EUR/kWh and 0.07 EUR/kWh, compared with 0.04 EUR/kWh and 0.03 EUR/kWh in the baseline low-cost case. This confirms that favourable hardware and installation costs alone are insufficient to ensure low infrastructure-related LCOC. Poor utilisation can offset, or even overcompensate, the benefits of low infrastructure costs, especially during the early deployment phase.

The estimated cost ranges should be interpreted as infrastructure-related LCOC, not final end-user charging prices. They include annualised capital expenditures and operating expenditures for charging infrastructure but exclude electricity procurement, taxes, levies, land costs and profit margins unless explicitly stated otherwise. This distinction is important because infrastructure-related LCOC is only one component of the final charging

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price, but it is central for comparing charging concepts and assessing the sensitivity of MCS economics to utilisation and station design.

This study does not provide a horizontal comparison between electricity-based charging infrastructure and hydrogen refuelling infrastructure for heavy-duty vehicles. Its scope is limited to megawatt charging infrastructure for battery electric trucks. A comparable assessment of hydrogen refuelling infrastructure over the same time horizon would require a separate modelling framework, including assumptions on station design, utilisation, hydrogen production and supply chains, storage and distribution concepts and regional deployment conditions. Such a comparison is therefore beyond the scope of this manuscript.

Several limitations should be considered. First, the demand simulation is based on empirical one-day driving profiles from Germany and does not capture potential long-term changes in logistics operations, such as altered route planning, regulation, load consolidation or automated driving. Second, the analysis is deterministic and addresses uncertainty through low- and high-cost assumptions and utilisation trajectories, rather than through a full probabilistic uncertainty analysis. Third, the cost model focuses on core infrastructure components and does not explicitly include land costs, labour costs, supporting energy storage systems or other site-specific local constraints. These components can be relevant in individual deployment contexts and may vary substantially across regions, station locations, land markets, permitting conditions, construction requirements and grid situations. Including them as separate parameters would require location-specific assumptions that are not available consistently for the analysed charging network. The reported values should therefore be interpreted as infrastructure-cost estimates within the stated model boundaries, not as complete site-specific implementation costs. Actual project costs may differ where land acquisition, local labour costs, civil works, buffer batteries or additional energy management systems are required. The transferability of the results beyond Europe should therefore be assessed cautiously because operating conditions, mandatory breaks, electricity tariffs, grid connection practices and regulation differ across regions. Nevertheless, the qualitative conclusions are likely transferable: depot charging is expected to dominate total charging demand, public MCS infrastructure will be essential for long-haul use cases and utilisation will remain the key determinant of infrastructure economics.

The results are relevant for both policy and market actors. For policymakers, they indicate that early support for high-power infrastructure may be warranted despite initially low utilisation, because long-haul electric trucking requires a minimum public charging network. For infrastructure operators and logistics companies, the findings highlight the importance of coordinated rollout, demand aggregation and sufficient station throughput. Future work should integrate infrastructure cost modelling with more detailed operational strategies, regional grid constraints and realistic market diffusion pathways for heavy-duty electric vehicles.

5. Summary and Conclusions

This study assessed the future demand and infrastructure-related costs of megawatt charging systems (MCS) for battery electric trucks in Europe. By combining empirical truck operation data with a techno-economic cost model, the analysis links temporally resolved charging demand to annualised MCS infrastructure costs and the infrastructure-related levelised cost of charging (LCOC). The results show that MCS is not expected to dominate truck charging overall. Most charging events can be covered by depot charging at comparatively low power levels, while MCS is primarily required for long-haul operation and for charging during intermediate breaks. For long-haul trucks, public high-power charging becomes strategically important because a large share of MCS demand occurs away from depots and during daytime operating hours.

The main economic finding is that infrastructure utilisation is the central driver of infrastructure-related LCOC. In the early deployment phase, annual MCS infrastructure costs remain high relative to delivered energy because installed capacity is used only partially. As electric truck adoption increases and station throughput improves, infrastructure-related LCOC declines substantially. Under the analysed assumptions, infrastructure-related LCOC falls from 0.27 EUR/kWh to 0.07 EUR/kWh in the high-cost case and from 0.173 EUR/kWh to 0.034 EUR/kWh in the low-cost case between 2025 and 2050. Annual MCS infrastructure costs are dominated by capital expenditure, while operational expenditure remains a smaller but persistent cost component. These results indicate that MCS infrastructure can become cost-competitive in the long term, but only if rollout and demand growth are sufficiently coordinated.

The technical contribution of the study is threefold. First, it translates empirical truck driving profiles into temporally resolved charging demand while preserving observed trip sequences, stop durations and operational constraints. Second, it distinguishes between depot charging, conventional fast charging and megawatt charging, thereby showing which parts of truck operation require public high-power infrastructure. Third, it connects simulated charging demand to a transparent infrastructure cost model that separates investment costs, operating costs, utilisation assumptions and delivered energy. This contribution differentiates the study from earlier work that primarily quantified technical feasibility, charging demand or infrastructure locations. The present analysis instead evaluates under which utilisation and cost conditions public MCS infrastructure can become economically viable.

The practical implication is clear: infrastructure planning for electric trucks should not treat MCS as a universal charging solution. Depot charging should remain the backbone of truck electrification wherever vehicles have sufficient dwell time, while MCS should be deployed selectively for long-haul corridors, logistics nodes and locations with high expected charging throughput. For policymakers, this means that early support may be justified to overcome initial underutilisation and to ensure minimum network coverage for long-distance operations. For charging operators and logistics companies, the results underline the importance of demand aggregation, site selection and coordinated rollout. Poorly utilised MCS stations will be expensive, whereas well-located stations serving concentrated long-haul demand can reach much lower infrastructure costs per kWh.

Overall, the study shows that the transition to battery electric long-haul trucking requires both depot-based charging capacity and a targeted public MCS network. The economic challenge is less the technical feasibility of megawatt charging itself than the timing, sizing and utilisation of the infrastructure. Future work should therefore combine cost modelling with spatially explicit station placement, local grid constraints, charging price design and more detailed representations of fleet operators' charging strategies.

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