# Barriers and Enablers for the Implementation of Megawatt Charging Systems

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Pjotr Visser p.visser2@student.vu.nl

Student number: 2776802

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University: Vrije Universiteit Amsterdam

Company: Cenex Nederland

Internship coach: Jorden van der Hoogt jorden.vander.hoogt@cenexgroup.nl



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## Abstract

The transition to electric trucks in the heavy-duty logistics sector is essential for reaching climate goals, but current charging infrastructure is not sufficient for long-haul operations. Megawatt Charging Systems (MCS) offers a solution with charging speeds that make it possible to charge a truck within the obligated rest period within the EU, this technology is currently in the demonstration phase. This research identifies the technical, financial and policy obstacles to large scale implementation on public charging hubs by charge point operators (CPOs), and lists the potential solutions suggested by practice and literature.

A qualitative study was done combining the findings of interviews with important actors within the heavy-duty charging infrastructure ecosystem, analysis of corporate and policy documentation and the Truck charging symposium by Fraunhofer in Berlin. In addition to this a quantitative study to analyse the financial feasibility was done using the *Charging Infrastructure Business Case Assessment Tool* (CIBCAT) developed by Cenex.

The technical results point to grid congestion and the high costs charged for peak power use as most critical obstacles to implementation. To overcome these issues the addition of battery energy storage on-site is essential, with the addition of renewable energy sources making the business case more attractive. Another technical shortcoming is found in the lack of digital infrastructure to plan and book charging slots, which is necessary to get efficiency high enough to compete with diesel trucks. On the financial side the sector is facing a 'chicken and egg problem' with low use rates in the initial phase but the need for existing infrastructure before logistic carriers start using battery electric trucks. On policy-level, the current alternative fuel infrastructure regulation falls short because it does not take MCS charging power into account and ignores the differences in charging needs within the European Union.

The research concludes that to get to large-scale implementation of MCS, CPOs need to focus on developing an advanced booking system with smart integrations of trucks and traffic data, as well as the use of BESS. On the policy side the need for streamlined grid connection procedures by governments and the prolongation of financial incentives in favour of battery electric trucks are found necessary to get to implemented MCS and the electrification of long-haul trucking.

# Contents





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# 1 Introduction

## 1.1 Technology and IPO model

Passenger cars are getting increasingly electrified, and the charging protocols are keeping up, with A/C charging up to 22 kW and DC (CCS 2) up to 500 kW (Keller & Tetik, 2025). While this is sufficient for these cars, it is not quick enough for bigger vehicles like trucks and busses that need to travel large distances. This type of vehicle needs a battery of approximately 600 kWh while a passenger car uses an average battery of 70,7 kWh (Earl et al., 2018; Li et al., 2024). This means it takes a significantly longer time to charge at low power levels, which is not sufficient for long-haul trucking since time is an important factor for logistic carriers. Megawatt Charging Systems (MCS) is a new protocol for charging vehicle batteries. It can charge at a theoretical rate of up to 3.75 MW and is therefore a lot more suited for long haul electric trucks.

MCS uses a new charger and charging port and needs sufficient electric infrastructure to be implemented on large scale. Therefore, steps need to be made on both the truck producing side as the infrastructure. This means OEM's need to build trucks compatible with MCS, but electric infrastructure operators also need to prepare their grids for substantial loads (Keller & Tetik, n.d.).

*IPO model*

While this project is done on behalf of Cenex Nederland, this is not the relevant organization to make an input process output model for because it is a research and consultancy company. Since this project is performed from the perspective of charging point operators (CPOs), this type of organization's business model is most relevant to the project. This is visualized in an input process output model, a model for visualizing an organizations activities. The model uses inputs, such as resources, staff and capital and shows what activities the organization performs to get to certain outputs.

For CPOs the primary processes entail building charging stations and operating these charging stations (Gillström et al., 2024). To be able to perform these activities, resources are needed, these can be divided in general resources and CPO specific resources. The general resources are capital and staff, as these are necessary for all organizations with a physical product. The resources needed specifically for CPOs are hardware like chargers, energy and grid connection possibilities (Gillström et al., 2024). Hardware is sourced from companies that produce chargers and other necessary equipment. To obtain grid connection possibilities and energy, a process is needed, in figure 2 this is named 'cooperation with energy providers and grid managers.' The last resource necessary for CPOs to function is demand from logistic carriers. This is used in the activity of planning where to build new charging stations together with grid connection possibilities. In figure 2 the complete input process output model is visualized.

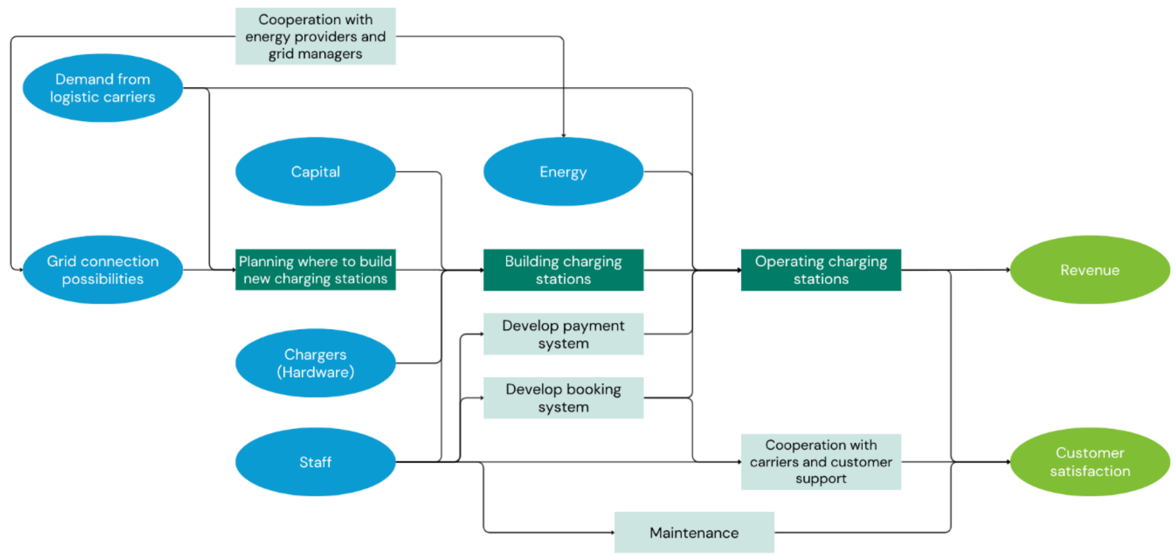


*Figure 1 Input Process Output model for MCS CPO. blue bubbles are inputs, dark blue green are primary processes, light green are secondary processes and green bubbles are outputs*

As seen in figure 2 above, CPOs perform other activities apart from the primary process of building and operating charging stations. These secondary activities can be divided in software, cooperation with customers and maintenance. Software is a very important component in operating a charging system, because charging stations need to work with a very efficient booking system. This is necessary because charging stations need to be in use for most of the time to be cost effective (Gillström et al., 2024).

Cooperation with customers is also of big importance to CPOs, as the logistical companies can think with the CPOs about where to build new stations.

The last side process is maintaining the charging stations for optimal performance and to prevent fallout (*CPOs, Charge Point Owners, and EMSPs explained | EVBox*, n.d.).

## 1.2 Position of technology and project within the technological innovation chain

Cenex is doing a 4-year research project on Megawatt Charging Systems together with partners across Europe called MACBETH (*Multipoint Megawatt charging for battery electric truck hubs*, n.d.). This project aims to address the technical, social and economic challenges connected to mass deployment across Europe. The goal of this is to help get MCS to the next stage of the technological innovation chain i.e. where MCS currently lies on the path from research to commercial valuation and continuous improvement. The Technological Innovation Chain is shown in figure 1 below. In the stages research and development there is no fully working product yet. From the demonstration phase the product gets caries out in niches and after that will be widely adopted and upscaled. In the continuous improvement stage, the technology undergoes incremental innovations but doesn't get adopted by a larger or new market.

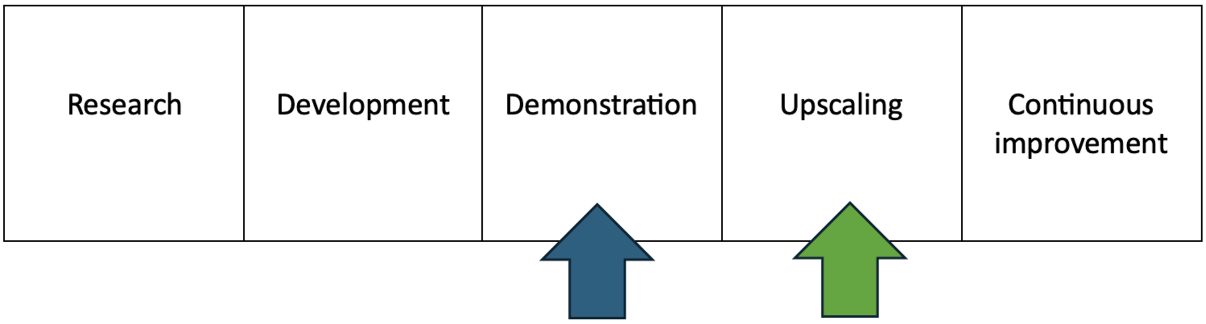


*Figure 2 Technological innovation chain with MCS at blue arrow and project aim at green arrow*

As shown in figure 1 with the blue arrow MCS is currently in the demonstration phase. This means the technology is ready for the market on a technical level but is not yet used on larger scale than very small niches and protected environments.

The green arrow shows the focus of this research project, which is upscaling. This research project aims to provide knowledge to help MCS to enter the upscaling phase. This phase entails market introduction on a commercial level and access to the full potential market for MCS.

MCS is already a working product, with a functioning charging speed of 1.5 megawatts (Li et al., 2024). While this is not yet as fast as the theoretical limit of 3.75 MW, this is enough to be classified as MCS and is significantly faster than the next best, CCS 2, which operates at a maximum of 500 kW. This suggests MCS has surpassed the development stage and entered the demonstration phase. This is supported by the research happening at this moment, like Macbeth. Macbeth is working on two demonstration sites in Belgium and in Sweden, to find out about the operating conditions, user needs and business cases (*Macbeth – Multipoint Megawatt charging for battery electric truck hubs*, n.d.). This research is done in a consortium, which includes Milence, a Charge Point Operator for heavy-duty EVs who aims to implement MCS in their charging locations in the future (Milence, 2025). Since it is not commercially available yet, MCS is not yet in the upscaling phase either, therefore it is currently in demonstration phase.

This project aims to identify future obstacles in implementing MCS worldwide on the technical, economical and policy levels. This knowledge contributes to MCS entering the upscaling phase.

## 1.3 Research setup

The implementation of the technology MCS is dependent on various factors on different sides of the sociotechnical environment. These can be divided into technical requirements, financial requirements and policymaking requirements.

On the technical side, obstacles can be found in the availability of electric trucks compatible with MCS. A problem already found in this subject is that it is currently not feasible to convert CCS compatible trucks to MCS compatible trucks, which means MCS could only be available for a very small part of trucks on the road (*Workshop Insights: Accelerating Megawatt Charging Systems Deployment for Heavy-Duty Vehicles – ALICE Alliance for Logistics Innovation through Collaboration in Europe*, n.d.). Another technical obstacle already found is the fact MCS needs a lot of grid capacity, especially when using multiple chargers at the same location (Keller & Tetik, 2025).

This directly ties to a financial obstacle found in a living lab project by TNO. This project found that in the Netherlands it is hard to get a positive business case when using more than 1750 to 2000 kW because the grid connection costs increase by a higher rate from this point (Verbeek et al., 2025a). While this project only tests CCS chargers, this will also apply on MCS because these chargers use even more power.

On the policy side, MCS requires a shift of long-haul transport from diesel to electric. Since this is not immediately the economically favourable choice for freight companies, incentives from governments like subsidies are necessary to get BETs closer to financial parity with diesel trucks and make implementation of MCS possible (Serrano, 2025).

This research project was done by looking at the implementation of MCS from a single perspective. This is to make the research less broad, as it is not feasible to look at the implementation of MCS from the perspective of every actor within the MCS ecosystem.

The ecosystem for heavy duty truck charging is comparable to that of electric passenger cars, except for the customers. The ecosystem is visualized in figure 3, where the logistic carriers replace the EV driver in this figure. Another stakeholder missing from this figure that is important for MCS are the OEMs. The OEMs are an important stakeholder for MCS since it is currently in the demonstration phase and for broader adoption, cooperation with OEMs is important as the vehicles need to be able to charge with MCS.

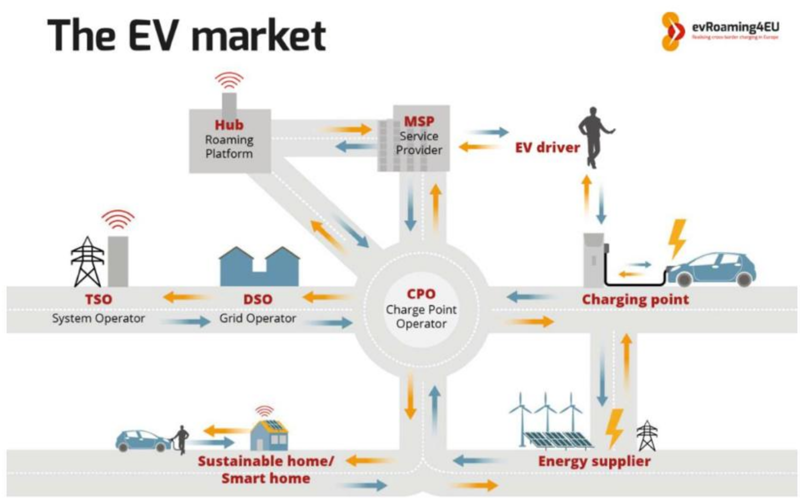


*Figure 3 The EV market visualised (Rijksdienst voor ondernemend Nederland et al., 2021)*

In this project the focus is on the CPO, as this is the stakeholder most centred in the ecosystem, with ties to all other actors. The CPO also has a direct impact on the implementation of MCS since they are the ones connecting the logistic companies to the megawatt charging systems.

Additional research has shown insights on technical, financial and policy levels. On the technical side, more obstacles surrounding the power supply have come to light. The two actors in the energy infrastructure in Europe are transmission system operators (TSOs) and distribution system operators (DSOs). The TSOs are the organizations connecting Europe's energy infrastructure on high voltage grids. The DSOs are the organizations distributing the energy to industrial, residential and commercial entities (DSO, 2025). The DSO is also responsible for distributing and building grid connections, which are necessary for CPOs to build new charging stations. A very important obstacle for CPOs is that there are too few grid connection possibilities (E. C. A., 2025). This problem is tied to the fact that grid improvement projects take significantly more time than renewable projects like charging stations (E. C. A., 2025). This leads to less balance between chargers and grid connections in the future and will be a source of obstacles for CPOs to implement MCS. Another problem is the need for stable high-power outputs by CPOs to work at optimal efficiency (Milence, 2024). This may lead to the need for energy storage at charging site to support charging at moments the grid can't handle the power output (Milence, 2024). Another thing that could help with this problem could be a better view of where the new grid connections can be found, so the grid is being used optimally (Staats, 2025).

On the financial level, the grid also is a source of obstacles. The instability of the grid makes for a higher total cost of ownership (Milence, 2024). The reason for this is that for CPOs, it is necessary to work on a tight schedule for optimal use of the chargers. To be able to plan the charging sessions best, a stable power output is of high importance. Another obstacle is the risk of high total cost of ownership because of high peak energy usage. Currently there is a fee based on annual peak energy use, which means the costs of energy is not just based on volume, but also on peak use (Milence, 2024). It is also interesting to look at the business case for OEMs, since this has a lot of influence on the demand for CPOs.

On the policy side, the issues are reflected by the issues stated above. Investments are necessary for grid connections on the places where CPOs want to build their charging stations. In Europe, these grid connections will be needed along the Ten-T network, this entails the most used on-road transport routes through Europe (EURELECTRIC, 2025). To do this, Alternative Fuel Infrastructure Regulation (AFIR) is set up, an incentive to have charging stations with a minimum capacity and maximum range between charging stations along Ten-T (Ragon et al., 2022). It is necessary for DSOs to invest in the energy grid along Ten-T to make AFIR happen (Milence, 2024).

Another issue is that renewable energy sources and charging hubs are currently separated, while a more direct link may work for CPOs, without the need of higher grid capacity, since these take significantly more time as getting a grid connection is inefficient (E. C. A., 2025).

These findings confirm that the obstacles on the levels of the socioeconomic environment in the first research question are relevant. Since the project is done from the CPO perspective, the following research question was formulated:

***'What obstacles at the technical, financial and policy levels influence the large-scale implementation of Megawatt Charging Systems from the perspective of CPOs, and what strategies are suggested in literature and practice to address them?'***

### *Sub questions*

The obstacles for implementation in the technological perspective will be found using the following sub question:

> *'What are the most important technical obstacles influencing the large-scale implementation of Megawatt Charging Systems from the perspective of CPOs?'*

This question aims to find the obstacles by looking at technical requirements needed for implementation of MCS. The answer to the question will also provide information about the priority order of these obstacles.

To address the financial side of the sociotechnical environment surrounding MCS, the same formfactor is being used as the first sub question. This question is:

> *'What are the most important financial obstacles influencing the large-scale implementation of Megawatt Charging Systems from the perspective of CPOs?'*

This question aims to find obstacles by looking at the business model of MCS and will also use a quantitative method developed by Cenex to evaluate the business model.

The third question will be about the policy side of the sociotechnical environment. It aims to find the required help needed from governments and other policymakers. The question is formulated as follows:

> *'What are the most important policy obstacles influencing the large-scale implementation of Megawatt Charging Systems from the perspective of CPOs?'*

The three questions formulated above are all about identifying the obstacles for the implementation of MCS. The three different perspectives of the sociotechnical environment form logical subjects for these questions. They also provide a priority order for the last part of the research project. This is finding possible strategies to overcome these obstacles. For this, another sub question is formulated:

> *'What strategies are proposed in literature and practice to overcome these obstacles and enable the large-scale implementation of Megawatt Charging Systems?'*

These questions' answers together cover the information necessary to answer the research question. For the first three questions, all levels from the multilevel perspective are taken into account.

# 2 Literature

## 2.1 Introduction and framework

As climate change creates increasing challenges for the world, the energy transition from fossil to renewable energy sources gets more urgent. The transportation sector has had a difficult challenge in reducing their carbon emissions (Jones, 2024). The heavy-duty vehicle transport sector puts out more than 25% of the greenhouse emissions of all road transport (Panciu et al., 2024). This results in the need for transition from diesel trucks to trucks with electric motors. This can be both fuel cell electric trucks (FCETs) and battery electric trucks (BETs). Although, BETs seem to end up being the dominant technology because the costs of FCETs are simply higher (Albatayneh et al., 2023; Burke & Sinha, 2020). In this project the multi-level perspective will be used as a lens to study the introduction of MCS as a niche technology driving the transition from diesel trucks to battery electric trucks for long haul trucking.

The multi-level perspective (MLP) is a framework used to analyse technological transitions within a system (Geels, 2002). This system is visualized in figure 4 and shows three levels: technological niches, sociotechnical regimes and landscape developments. A regime is described as a combination of organizational and cognitive routines (Nelson & Winter, 1985). This means actors like companies and institutions that work within a regime tend to share behaviour and vision, a regime can be a business sector. The landscape consists of large external factors like culture, politics and other societal factors that cannot be changed by a single actor. The landscape developments influence the regime and cause the need for change by the regime which leads to transitions. One of the most important landscape developments that's causing the transition to renewable energy sources is climate change (Jayaraj et al., 2024). The technological niches consist of new technologies that drive transitions and succeed when they fit together with the needs of the regime.

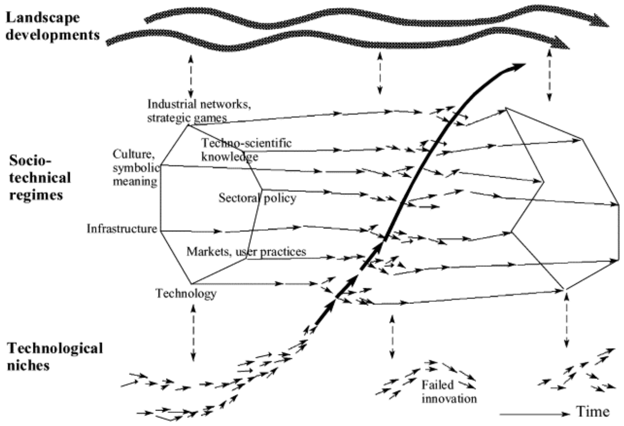


*Figure 4 The multi-level perspective of technological transitions (Geels, 2002)*

Empirical analyses with the multi-level perspective can do justice to the complexity of real-world developments (Geels, 2002). The MLP framework has been used in a variety of studies analysing transitions to zero-carbon solutions (Berkeley, 2017; Kanger, 2021).

In the following literature review the factors that influence the implementation of MCS are categorized according to the MLP framework.

## 2.2 Technical aspects

*Charging behaviour and power demand*

Most Battery Electric Trucks (BETs) will only make use of chargers at the depot, because most trucks don't drive such long distances per day that on route charging is necessary (Speth & Plötz, 2024). However, for long haul BETs with a daily driving distance higher than 805 km, a megawatt level charging speed will be necessary (Speth & Plötz, 2024). These long haul heavy duty trucks represents less than 15% of the truck fleet but is responsible for 65% percent of the CO2 emissions of all trucks in Germany (Burges et al., 2021).

According to EU regulation truck drivers have to take a mandatory 45 minute break after every 4.5 hours of driving (Schneider et al., 2023). This means that for the battery to charge enough to be able to drive for the next 4.5 hours, charging speeds between 761kW and 2802 kW are necessary. In this range, 979 kW was found as the best charging power to be fully charged within 45 minutes, if higher power is used, the battery would be charged in less than 45 minutes so then the rest time would not be over (Schneider et al., 2023). Higher charging power could result in an optimized utilization rate as no truck would need to be at the charger for more than 45 minutes.

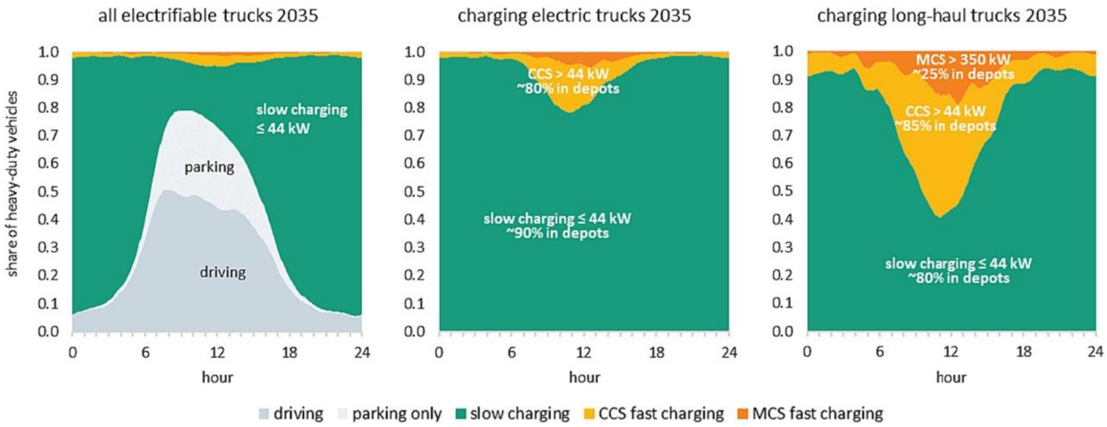


*Figure 5 Charging behaviour of electric trucks during the day*(Speth & Plötz, 2024)

Over the whole day, MCS will be used mostly during the day since there will be virtually no high power charging needed during night time (Speth & Plötz, 2024). The use of MCS chargers will likely be concentrated in a small timeframe since it will be used to charge on route, and drivers start their day approximately at the same time. This is visualized in figure 5 above, it shows the charging behaviour for trucks. The graph on the right is most relevant to this research project as it solely includes long-haul trucks. The hour with the highest charging volume is between 12:00 and 13:00, with 6.07% of total daily charging demand (Speth & Plötz, 2024). This means for CPOs that there will be a small amount of the day where megawatt scale charging is needed. The MCS standard is designed to provide a range of charging power between 440kW and 3.75 MW (Bohn, 2023), this means also slower charging speeds can be performed with the MCS chargers so the charger could also be used at times where megawatt level charging is not necessary. This charging behaviour is a result of existing dominant regime with trucks driving during the day and charging during nighttime. The current state of technology keeps this regime intact, but with possible future introduction of autonomous trucks this may change (Adegbohun et al., 2023).

### *Energy supply and grid constraints*

Charging at megawatt level requires a high spatial energy capacity of 0.5 to 1 MW/ha. This is 10 to 20 times more than normal capacity per surface area than in 2021 (Burges et al., 2021). This means high-capacity grid connections are needed for stations using MCS.

The reason for this is that the power use of MCS charging stations has a high volatility (Stith et al., 2025). This causes high peak energy use for which a high-power grid is necessary. On the other side, when less power is used, the distribution system operators need to deal with overcapacity (Stith et al., 2025). Stith et al suggests using Battery Energy Storage Systems (BESS) for peak shaving, so a less high-power grid connection can be used while still being able to charge at high power. This battery system would be charged at times when the grid has an overcapacity, and when a truck is charging this energy will be used to deliver extra power as addition to the grid. In this way less peak power use is needed.

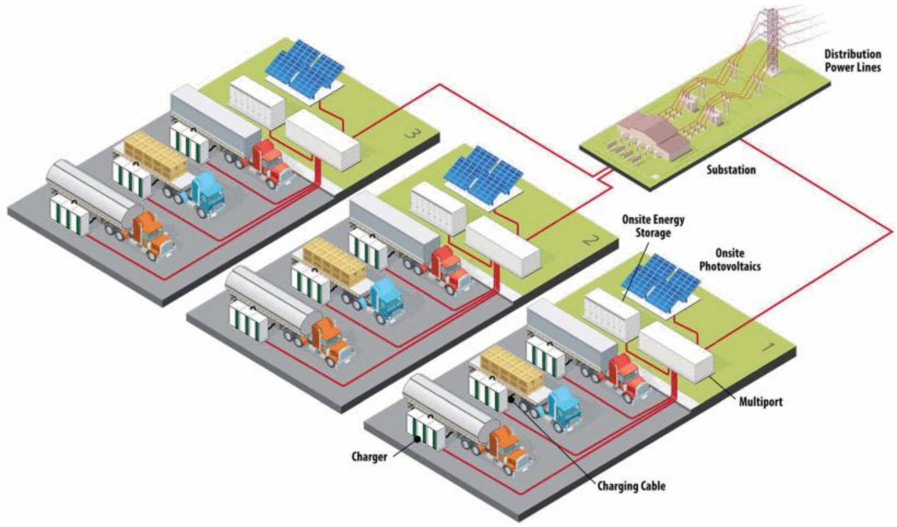


*Figure 6 An example of a charging hub layout with BESS and RES-E added to the system (Moorthy et al., 2022)*

Another addition to the charging station suggested in literature is renewable energy sources electricity (RES-E) (Moorthy et al., 2022). This is used together with the battery and can be used to charge the battery at times no truck is charging. An example of a charging hub with BESS and RES-E added is shown in figure 6. This could also prove to be useful for directly charging the truck as the peak of RES-E production is done during midday and the lowest RES-E production is done at night (Mulder, 2014). This works together well with the charging demand found by Speth & Plötz. Energy supply distribution could be one of the factors enabling the large-scale implementation of MCS as it lowers the need for high-capacity grid connections. The need for addition of different energy sources to the electricity grid is supported by Zuo and Li (Zuo & Li, 2024).

In a study in the UK along a highway, tests have been performed to find out whether the grid currently is sufficient or not. The results pointed out that grid upgrades are necessary to be able to provide enough energy for charging electric trucks. They have also simulated a situation where they added RES-E and BESS to the grid. While this did improve the situation, it turned out it didn't fully cover the capacity gap. More energy supply distribution is necessary. (Alharbi et al., 2024) From the MLP perspective, these technological innovations can be understood as niche developments.

### *Digital infrastructure*

Another technical issue that need to be addressed is the need of an efficient booking and payment system. This is something where logistic carriers and CPOs need to collaborate and share data (Govik, 2024). This collaboration is necessary as traffic and other factors make it difficult to give an exact estimation of when and where a truck will charge. The study by Govik suggests a platform where traffic data and available charging infrastructure are combined, this would entail collaboration with tech giants able to build and manage these complex systems. In this platform payments could be standardized and information about pricing and amenities would also be incorporated. This need for digital infrastructure can be seen as a pull from the regime but will have to come from technological niches.

### *Safety risks*

Safety is also an important factor in the implementation of MCS in charging hubs. High power use comes with safety issues like grid overload, component overheating and short circuit risks (Pawlak, 2025). An intelligent load management system and solutions like liquid cooling to keep cables from melting are necessary (Pawlak, 2025). Since charging networks become smart and connected, cybersecurity also plays a part in the safety of charging infrastructure. This creates the need for digital certificates, encrypted communication and threat monitoring (Pawlak, 2025).

Another safety concern is the fact that electric vehicles (EVs) are susceptible to catching on fire (Sun et al., 2020). When an EV catches fire, it is very difficult to contain as the battery can reignite and is hard to cool down (Sun et al., 2020). As BETs have large batteries compared to regular EVs this problem gets bigger and need to be considered when building a charging station. The CPO must take measures for fire hazards.

## 2.3 Social economic aspects

### *2.3.1 Financial factors*

The large-scale implementation of MCS is dependent on both financial factors and policy factors. To start with financial factors, the economic feasibility is highly dependent on the taxation of grid connections. Countries in Europe use different methods for taxation of grid connections, so costs of installation of a station may vary (Hildermeier & Jahn, 2024). In a living lab study by TNO in the Netherlands, this issue was also pointed out. For grid connections higher than about 1750 kW to 2000 kW the grid connection costs in the Netherlands rise significantly, which makes the business case for large charging stations with more than one MCS charger less favourable(Verbeek et al., 2025).

Another financial obstacle is the primary phase, with a combination of high upfront costs and low utilisation rates. Because BETs will only be usable with a dense charging network, the capital expenditures (CAPEX) are high (Otteny et al., 2024). This makes a high utilisation rate necessary to overcome too high total cost of ownership (TCO) for CPOs, which cannot be expected in the initial phase of BETs (Otteny et al., 2024).

However, forecasts indicate economic advantage of TCO of BETs compared to diesel trucks and also compared to other alternative fuels (Claes et al., 2022). A forecast of the TCO of BETs divided by that of diesel trucks is visualized in figure 7, indicating that after 2030 the TCO of BETs could be less than that of diesel trucks. This indicates that logistic carriers will shift from diesel trucks to BETs in the future. This gives insurance for CPOs that demand will grow, and investments can be earned back.

However, another study suggests that the TCO of BETs could be viable in the future, but that for long haul heavy duty trucks this is very reliant on policy measures in favour of BETs (Jahangir Samet et al., 2024; Serrano, 2025). These policy measures include financial incentives like lower taxation on electricity and toll fare lowering, but the study also emphasizes the need for a dense network of MW capacity charging stations (Jahangir Samet et al., 2024). The changes in the TCO of BETs compares to diesel trucks happen in the regime but are driven by technological niches that make the TCO of BETs lower. It could also be incentivised from within the regime by regulation and financial incentives.

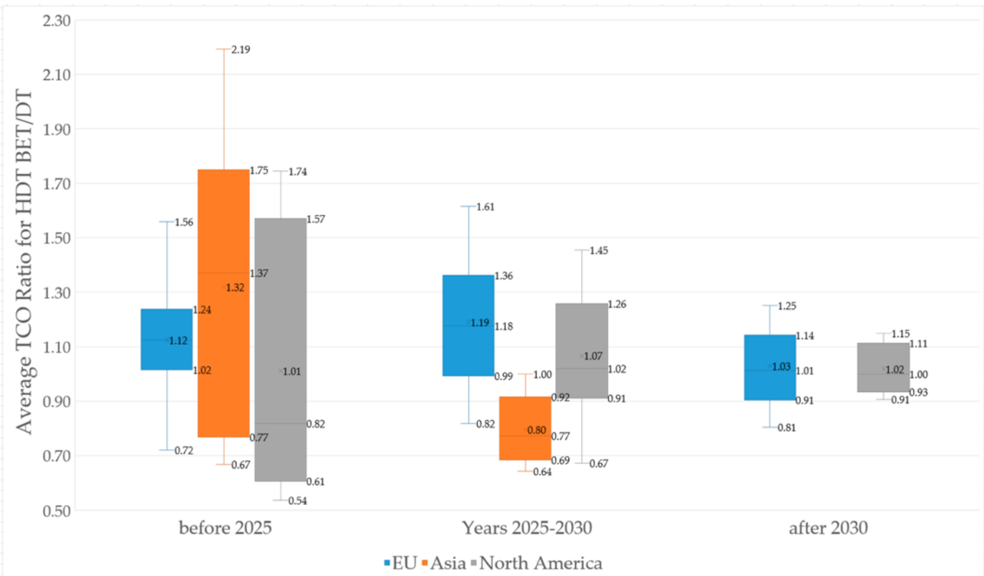


*Figure 7 The future expectation of the TCO of BETs divided by the TCO of diesel trucks (Danielis et al., 2025)*

### 2.3.2 Policy

On the policy side, one important regulation is the Alternative Fuel Infrastructure regulation (AFIR). In this, the plan is formulated to make sure a dense network of public chargers along the Trans European Transport Network (TEN-T) exists by 2030 (Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the Deployment of Alternative Fuels Infrastructure, and Repealing Directive 2014/94/EU (Text with EEA Relevance), 2023). In AFIR, the minimum capacity for a charging station along TEN-T core network in 2030 is 2600 kW with individual charging power of at least 350 kW. The maximum distance between these charging stations will be 60 kilometres.

These charging powers will not be enough, since at least 798 kW of charging power is necessary to be able to charge in the mandatory break time (Schneider et al., 2023).

For a charging speed of 350 kW, CCS 2 chargers are sufficient, but for higher charging speeds MCS is the better alternative, with average charging power of 1100 kW (Shoman et al., 2023). The AFIR proposal is an example of the sociotechnical regime reconfiguring to the needs from the landscape.

Another policy related issue is the shortage of grid connections and the process of getting a grid connection in Europe. According to Milence, one of the CPOs planning to implement MCS in their charging stations, the time it takes to get a grid connection in Europe is too long (Milence, 2024). The waiting time for grid connections in European countries differs between 5 and 8 years (Roach, 2025). For CPOs like Milence, shorter waiting times are necessary to deliver the right capacity to comply the AFIR plans.

One of the reasons for the waiting times are this long is the fact that there is an increasing amount of connection requests from both energy users as renewable energy producers (E. C. A., 2025). Another reason is the fact that grid infrastructure projects take a lot of time compared to the building time of charging hubs and other energy users and producers (E. C. A., 2025). For instance, building charging hubs takes one to two years, while distribution grid projects take at least 5 years (E. C. A., 2025). This difference in project timelines in visualized in figure 8.

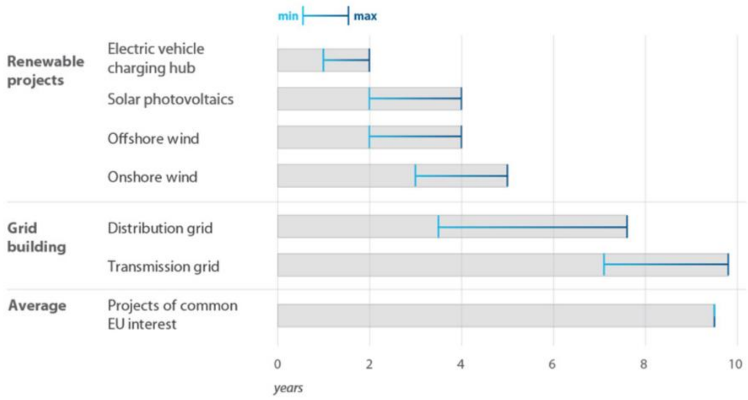


*Figure 8 Timeline for different energy projects (E. C. A., 2025)*

A less technical cause of the waiting time is the inefficiency of the procedures companies need to go through to get connected (Pató et al., 2024). The suggestion to help fix this issue is making the grid more transparent. This entails making grid capacity visible so companies like CPOs can take the availability of grid capacity in account when planning where to build new charging stations (Pató et al., 2024).

# 3 Methodology

## 3.1 Conceptual model

The conceptual model of this research project derived from the literature is presented in figure 4. It visualized the negative moderating effect of technical, financial and policy-related issues on the transition of megawatt charging systems from demonstration phase to large scale implementation by charge point operators.

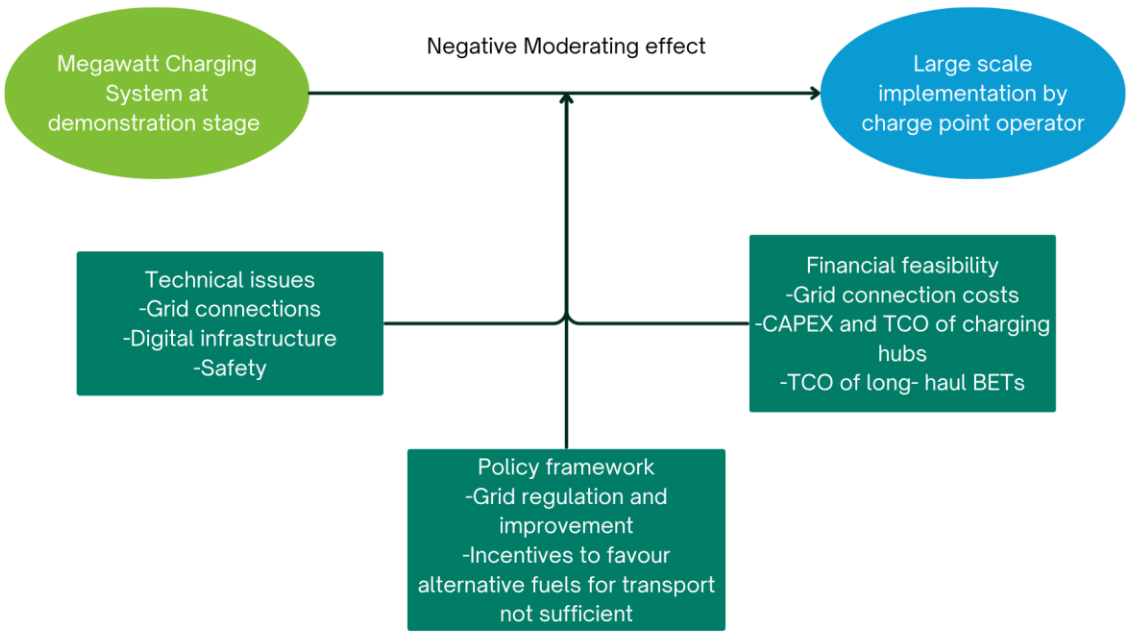


*Figure 9 Conceptual model visualising the negative moderating effect of technical, financial and policy factors*

The aim of this research project is to study the transition of megawatt charging systems from the demonstration phase, which the technology is currently in, to large scale implementation by charge point operators. In the literature study different factors were found that influence this transition from demonstration to implementation. These factors can be divided in technical issues, policy framework and financial feasibility.

From a technical perspective, multiple barriers have come to light in the literature study. The lack of capacity and shortage of grid connections forms an obstacle for MCS to be rolled out along the TEN-T network. Also, the absence of digital infrastructure for the booking system and payment system for truck charging has proven to be a barrier, as it will be complicated to manage with tight schedules of logistic carriers and dependency on traffic. Another issue that needs to be addressed is the safety concerns, not only on site but also on cybersecurity.

At the policy level, the lack of grid regulation and grid improvement is highlighted in the literature review. The current policy for the implementation of alternative fuels in the transport sector also turned out not to be sufficient for long haul trucking.

At the financial level, the combination of grid connection costs and the TCO of charging hubs also forms an issue. The implementation of MCS by CPOs is also dependent on the success of battery electric trucks as they need to have at least an equal TCO as diesel trucks.

All these factors found influence the implementation of MCS, so they have a moderating effect. Since they are inhibiting the transition from demonstration to implementation, it is a negative moderating effect.

## 3.2 Research plan

The conceptual model has shown the three clusters – technical, policy and financial - that influence the implementation of MCS. The empirical phase in this project aims to identify and analyse the barriers in each cluster. To do this, both qualitative and quantitative research is performed. The technical and policy issues are researched using qualitative methods and the financial analysis are done both by qualitative and quantitative research. The research plan is shown in figure 5 below.

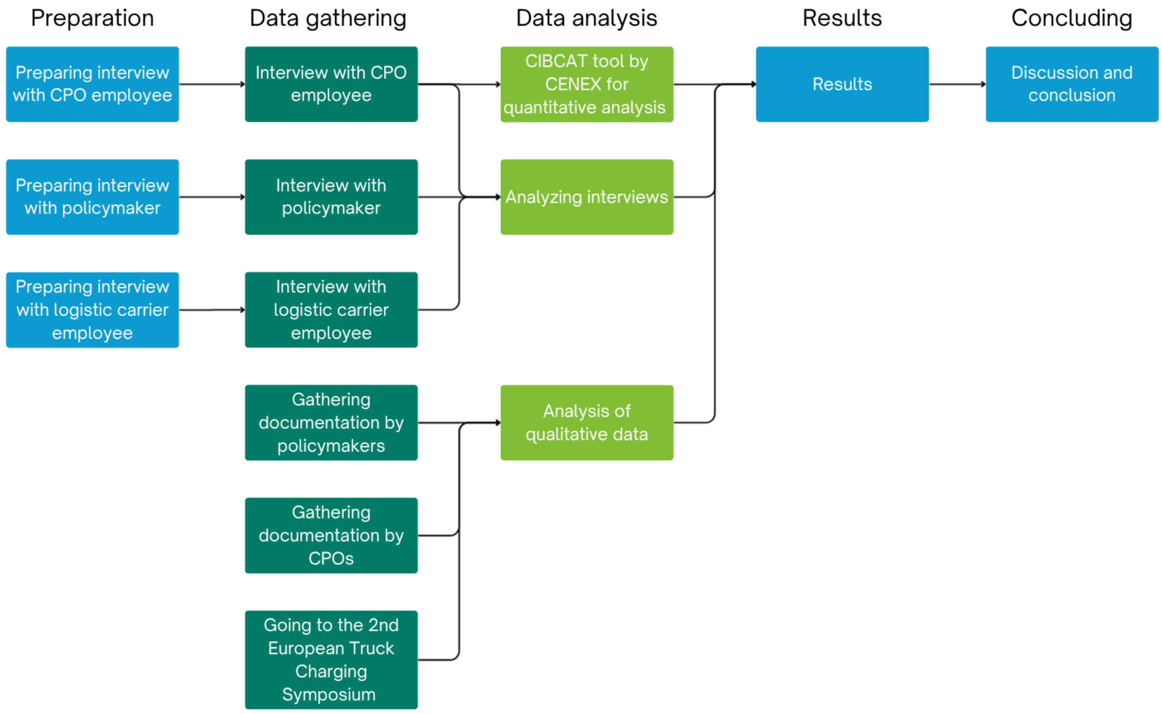


*Figure 10 research plan*

The qualitative research consists of interviews and the analysis of documents like white papers and policy papers. Another source of information that will be used is the 2nd European Truck Charging symposium. The notes made at the symposium together with the slides provided by speakers will be analysed.

The quantitative analysis consists of Cenex's Charging Infrastructure Business Case Assessment Tool (CIBCAT), this tool is used to assess the business case of a single public charging site. It gives an estimate of a cashflow statement for a period of ten years. This will be used to gain knowledge about the financial feasibility of MCS charging sites for charge point operators.

The research plan is ordered in phases, the first one being *preparation*. In this stage the interviews will be prepared and will be reached out to possible interviewees. For each interview the exact goals of the interview are determined and from that, questions are derived.

The next phase is *data gathering*, this is where the interviews will be performed and transcribed and documentation by policymakers and CPOs will be sourced. These documents mainly consist of whitepapers by CPOs and policy papers and proposals from countries in EU and the EU itself. The 2nd European Truck Charging Symposium in Berlin has been visited in September 2025, and the slides are be provided by speakers.

In the *data analysis* phase, the interviews are analysed to identify the obstacles and proposed solutions. The documentation sourced and the notes and slides from the symposium are analysed to find obstacles for implementation of MCS. In this phase also the CIBCAT tool is used to estimate the business case of implementing MCS and for this, information from the interviews with CPOs will be used as inputs.

In the *results* phase all findings will be documented and a comparison of the qualitative research of the interviews and the documentation by policymakers and CPOs will be compared. The results of the quantitative is also stated in this phase.

At last, in the *concluding* phase, the results are interpreted to draw a conclusion and answers to the research questions. This is compared to the findings of the literature study in the discussion. Recommendations for the implementation of MCS are stated together with suggestions for additional research.

### *Interviews*

The interviews that are performed in this project are based on certain profiles, since the exact appointments have not been made yet. Three profiles would be relevant for this project; someone working in a relevant position at a charge point operator, someone who works at a policymaker and an individual at a relevant position at a logistic carrier.

The profile of *the employee of the charge point operator* would be someone involved in the planning of the implementation of megawatt charging systems in their existing charging station or in new charging stations. This individual can give information on barriers the CPO has problems with for the implementation of MCS. It is also of importance to hear what suggestions the CPO have over overcoming these barriers and what they need from entities like DSOs and policymakers. Another goal of the interview is to get information about their plans for implementing MCS in their charging stations, which can be used to base the inputs for the CIBCAT tool on. This gives more accuracy to the quantitative analysis. The goal is to interview at least two people who work at different CPOs to compare their visions.

The *policymaker* profile is an individual who works at a government entity involved in regulating the decarbonization of road transport. This person can explain the current regulation and give information of the possible future incentives to favour BETs of DTs. This person can also give information on the grid regulations and policies to reduce grid constraints. It's necessary to interview at least one person at a policymaker on country level, because an EU body is out of reach and this person would still be able to give the relevant information.

At last, the profile of the *logistic carrier*, this is an individual involved in the transition from diesel trucks to BETs. The company this person works at needs to do long-haul routes along the TEN-T network. The aim of this interview is to find out the minimal charging infrastructure needs of logistic carriers for making the transition to BETs on their long-haul operations.

All interviews are semi-structured, as this left enough room for adding questions while still making sure certain answers will be found.

The interviews are analysed using a deductive thematic approach. The three themes of the conceptual model – Technical, Policy and Financial – served as the analytical framework for categorizing the responses from the interviewees.

# 4 Results

## 4.1 Technical findings

### *Introduction*

In this section the findings of the technical dimension are presented. These results are derived from the interviews performed, corporate documentation, policy documentations and the MCS symposium in Berlin. The research question these results answer is: 'What are the most important technical obstacles influencing the large-scale implementation of Megawatt Charging Systems?' The results also relate to the last research question about the solutions suggested in practice to overcome these obstacles. The dimensions within this section in the conceptual model are grid connection issues, digital infrastructure and safety. While these dimensions come from the literature review, also some new dimensions were found in the empirical study. The findings from the empirical study related to the technical dimension are listed in table 1. The sources indicate the information source it came from; 'I' means interview, 'D' means document and 'S' means symposium. The details of these sources can be found in appendix B, appendix C and appendix D.

Table 1 Findings on technical barriers for the implementation of MCS and proposed solutions and drivers to facilitate the large-scale implementation of MCS

| Findings | Sources |
|---|---|
| MCS is currently at technology readiness level 7-8 | I2, S6 |
| Net congestion is seen the largest technical obstacle to the large-scale implementation of MCS | I2, I3, I5, I6, D1, D3, D8, D10, S6, S9 |
| BESS is seen as crucial when charging at megawatt level speeds | I2, I3, D1, D8, S8, S11 |
| Innovative ideas are necessary and possible to deal with grid congestion | I3 |
| Smart charging solutions and smart booking systems are necessary when use of BETs rises | I1, D1, D2, D6, D9, D10, S6, S15, I5 |
| Uptime of chargers is very important for logistic carriers to transition to BETs, therefore MCS should be standard | S14, I1, S5, I5 |
| The design of charging sites needs to be modular to facilitate transition from MCS to CCS | D6, S7, S13 |
| The cooling system needed to facilitate MCS can be too loud | S9, S10 |

### *The charger itself and inertia of CCS*

The status of MCS is that it is working well and is tested (I2). High and stable charging speeds are already achieved with very little decline in power as the state of charge of the battery gets higher (I2). MCS chargers have already been implemented by Milence in three charging sites in Sweden and Belgium (S6). A charger manufacturer is currently in the phase of standardizing and applying for certification (I2). These things are indicators that the technology has reached technology readiness level 8, this means it is a full-grown technology ready to be adopted by the market. It also indicates no technical hurdles need to be overcome on the charger itself. MCS is more reliable than CCS and therefore should be implemented by OEMs before CCS gets too much inertia and becomes the standard (I5).

### *Connecting to the grid*

The issues related to the congestion of the electricity grid have proofed to be the priority. This problem is comprised in two different issues, getting the grid connection and having too little peak power to directly supply the trucks with energy. The issues with getting the grid connections on the technical level emerge from the lack of capacity and also the lack of visibility where there is still capacity (D1, D8). This leads to issues in planning new charging sites which leads to slower rollout of MCS.

The issues with the amount of peak power are caused by financial limitations (which will be discussed in the financial result section) and by the fact that on some places a grid connection can be bought but the capacity may not be there to supply multi megawatt power which is needed for MCS (D1).

In practice, the consensus is that to deal with this, the use of Battery Energy Storage Systems (BESS) is necessary and not optional for most charging sites (I2, I3, D1, D3, D8, D10, S6, S9). This BESS can draw consistent but low power from the grid to charge itself, which would not cause high peak loads. When a truck needs to be charged quickly the battery can discharge into the truck at megawatt charging speeds. This has been tested and proofed for 1.1 MW charging speeds (S8). It also makes the use of renewable energy sources RES more feasible, as there does not need to be a truck at the charger at the same time as the energy is being generated (S8). Other innovative solutions like cable pooling are also suggested but not yet worked out as regulation differs per country (I3, I5, I6).

### *Digital infrastructure*

Another technical obstacle more generally for BET charging is that logistic carriers value efficiency most and want to be able to charge when they need to (I1, I4, D2). The fact that arrival times at chargers is highly dependent on factors like traffic makes this more difficult as trucks can easily get there later than the charging time slot they may have booked (I1).

To combat these issues, an advanced booking and data system is needed (D2, D6, D9, D10, S6). This booking system would give real time data to truck drivers about the availability of chargers while also considering the arrival times of trucks based on traffic information. This system should also make use of the fact that most modern trucks are integrated into the Internet of Things (I5).

### *Messages for CPOs*

Some other findings important for CPOs to consider are the need for high reliability and uptime. This is something to make sure as it is key for logistic carriers to make the move to BETs and make use of MCS (I1, D9).

Another important thing to take into account that while now CCS is the standard, the expectation is that this will be just MCS in the future. To future-proof charging sites a modular design is suggested (D6, S7, S13).

A possible problem that is not very well-known is the loudness of MCS cooling systems. This has been tested and proven to be too loud to be near to for a long time (S10). This means without proper sound installation it is not possible for truck drivers to be in the cabin while the truck is charging.

## 4.2 Financial findings

*Introduction*

In this section the findings of the financial dimension are presented. These results are derived from the interviews performed, corporate documentation, policy documentations and the MCS symposium in Berlin. The research question these results answer is: '*What are the most important financial obstacles influencing the large-scale implementation of Megawatt Charging Systems?'* The results also relate to the last research question about the solutions suggested in practice to overcome these obstacles. The dimensions within this section in the conceptual model are grid connection costs, CAPEX of charging hubs and high TCO of BETs. While these dimensions come from the literature review, also some new dimensions were found in the empirical study. The findings from the empirical study related to the technical dimension are listed in table 2.

Table 2 Findings on the financial dimension

| Findings | Sources |
|---|---|
| Logistics sector is a TCO driven sector | I1, D2, D9, S11 |
| Charging at public charging stations is currently too expensive compared to private charging and diesel trucks | I1, S1 |
| Most charging (+- 80%) will be done at private chargers; public charging is only for long haul operation | I3, I4, S1, S2, S3 |
| The cost structure of grid connections creates financial problems as peak use is expensive | I3, D1 |
| Utilization rate is currently too low to become profitable | D9, S6 |

*TCO Dominance and Current Costs*

A primary finding, confirmed by multiple sources, is that the logistics sector is fundamentally TCO-driven (I1, D2, D9, S11). All investment decisions are weighed against their impact on the Total Cost of Ownership. Within this TCO-driven sector, public charging is currently not commercially viable. Sources state it is simply too expensive compared to both the operational cost of existing diesel trucks and the more affordable option of charging on private land near their depots (I1, S1).

*The dominance of Private Charging*

This financial reality leads to a clear strategic consensus among the respondents: most of the charging, estimated at 80% or more, will occur at private depots (I3, S1, S2, S3). Public charging infrastructure, such as MCS, is therefore seen as a solution primarily to facilitate long-haul operations where depot charging is not an option (S1, S2). This results in low utilisation because most truck operations do not need public charging infrastructure.

### *Structural Barriers to Profitability*

The findings identified two major structural barriers to a profitable public business case. First, the cost structure of grid connections creates significant financial problems. The high costs are not just for the initial connection (CAPEX), but are also driven by operational peak use tariffs, which make using large amounts of power (like 1MW) extremely expensive at specific times (I3, D1). Second, even if the infrastructure is built, the utilization rate of public chargers is currently far too low to become profitable in the short term (D9, S6). This creates a critical "chicken-and-egg" problem for CPOs seeking a return on their investment.

An innovative idea to overcome this is cable pooling, which suggests sharing a grid connection with a company that has opposite energy use hours from MCS, so during the night (I3). In this situation both parties pay for their own volume of energy but share the costs of their peak use.

## 4.3 Policy findings

### *Introduction*

In this section the findings of the technical dimension are presented. These results are derived from the interviews performed, corporate documentation, policy documentations and the MCS symposium in Berlin. The research question these results answer is: '*What are the most important policy related obstacles influencing the large-scale implementation of Megawatt Charging Systems?'* The results also relate to the last research question about the solutions suggested in practice to overcome these obstacles. The dimensions within this section in the conceptual model are grid regulation and improvement and incentivising companies to choose BETs over diesel trucks for long-haul operations. While these dimensions come from the literature review, also some new dimensions were found in the empirical study. The findings from the empirical study related to the technical dimension are listed in table 3.

Table 3 Findings related to policy from the empirical study

| Findings | Sources |
|---|---|
| DSOs are too slow in planning grid expansion and need to streamline the process of getting a grid connection together with transparency | D1, D2, D3, D4 |
| AFIR is not considered sufficient for long haul electric trucking and within the EU too many differences between countries cause AFIR to be too much for some countries and too little for other countries | D3, D7, S3, S13, I6 |
| CPOs need more assurance to be able invest in future projects and a standardised procedure to get grid connections | D2, I3, I5 |
| Smart location planning related to TEN-T needs to be better | D1, D2, S12 |
| Prolongation of subsidiary arrangements necessary to overcome financial barriers in the future | I3, D2 |

### *Grid Planning and DSO Bottlenecks*

A primary barrier identified by multiple sources is the process related to getting a grid distribution from distribution system operators (DSOs). The consensus is that DSOs are currently too slow in planning the necessary grid expansion to accommodate megawatt charging, while the TEN-T network is quite clear to use as planning framework (D1, D2, D3). There is a strong call to streamline the entire process of acquiring a grid connection, which is currently seen as a major obstacle (D1, D2, D3). This is made even worse by a lack of transparency, making it difficult for CPOs to identify where grid capacity is available, which slows down strategic planning (D1, D4).

### *Insufficiency of the Regulatory Framework (AFIR)*

While the Alternative Fuels Infrastructure Regulation (AFIR) provides a foundational framework, it is not considered sufficient to meet the specific demands of long-haul electric trucking a (D3, S3). The current goals are seen as a starting point, but sources indicate that some member states need to adopt higher targets as traffic is not divided equally within the EU (D3). The differences between countries are also found in the distribution of core and comprehensive TEN-T network. In countries like Finland only two roads belong to core TEN-T and most of the country relies on comprehensive TEN-T and this infrastructure less stimulated in AFIR (I6). Another specific issue is that the current AFIR text does not adequately define or include MCS, which creates uncertainty and prevents its formal integration into deployment goals (D7, S13). Also, the consensus is that for long haul trucking and being able to charge within the obligated break time at least 700-1000 kW is needed, while currently in AFIR 350+ kW is the highest requirement.

### *Investment Assurance and Strategic Planning*

From a CPO perspective, the findings highlight a clear need for more assurance to be able to commit to large-scale, capital-intensive investments (D2, D3, I3). The high financial risks, particularly related to grid connection costs, require a stable and supportive policy environment to unlock investment by CPOs (I3). This is directly linked to the need for smarter location planning. Sources indicate that infrastructure deployment must be strategically aligned with key logistics routes, specifically the TEN-T network, to ensure high utilization and a viable business case (D1, D2, S12). While this is already being done, more future planning is necessary.

## 4.4 Quantitative results

In the table in figure 12 the results from the quantitative business case analysis is shown. In appendix E the reasoning behind the analysis is explained. For CPOs it is important for a project to break even within a maximum of 3 years (see appendix A). To find out what needs to be the necessary utilization rate for each situation (grid only, grid + PV or grid + PV + Battery) was checked. In the upper half the corresponding break even years is shown and in the lower half the corresponding net present values are shown.

| | | | | |
|---|---|---|---|---|
| | Break even year | | | |
| | | Energy source scenario | | |
| | | Grid only | Grid + PV | Grid + PV + Battery |
| utilization rates | 5% to 10% | 5 | 2 | 2 |
| | 10% | 5 | 2 | 2 |
| | 10% to 15% | 5 | 2 | 2 |
| | 10% to 15% to 20% | 4 | 2 | 2 |
| | 15% to 20% | 3 | 2 | 2 |
| | 15% to 20% to 25% | 3 | 2 | 2 |
| | | | | |
| | | | | |
| | | | | |
| | NPV | | | |
| | | Energy source scenario | | |
| | | Grid only | Grid + PV | Grid + PV + Battery |
| utilization rates | 5% to 10% | 447.099,98 | 12207925,47 | 11932929,96 |
| | 10% | 447.099,98 | 12214110,39 | 11923163,5 |
| | 10% to 15% | 1014743,632 | 12529713,96 | 12231013,82 |
| | 10% to 15% to 20% | 1327577,776 | 12730136,85 | 12424379,24 |
| | 15% to 20% | 1526264,553 | 12846333,32 | 12520663,23 |
| | 15% to 20% to 25% | 1874317,661 | 13041455,71 | 12730109 |

*Figure 12 Table with results from CIBCAT analysis*

The conclusions that can be drawn from this analysis are that the biggest impact on NPV and breakeven time comes from the use of renewable energy sources and that a utilization rate that goes from 15% to 20% over ten years is needed to have a reasonable breakeven time.

# 5 Discussion

## 5.1 Discussion of results

To answer the main research question; What obstacles at the technical, financial and policy levels influence the large-scale implementation of Megawatt Charging Systems from the perspective of CPOs, and what strategies are suggested in literature and practice to address them? The results of the empirical study will de compared to the findings of the literature study. This will be done using the discussion scheme above. The themes are divided according to the conceptual model, with technical, financial and policy obstacles as influences on the implementation of MCS. In each theme, the proposed solutions to these obstacles are discussed.

*Technical aspects*

In the literature study it was found that the high power demand of MCS charging stations and the concentration of demand in the middle of the day causes high volatility of power use and the grid does not have the capacity to handle these peaks (Burges et al., 2021; Schneider et al., 2023; Speth & Plötz, 2024; Stith et al., 2025). In the empirical study was found the peak power use of MCS charging sites and capacity of grid connections forms a significant obstacle for the implementation of MCS (I2, I3, I5, I6, D1, D3, D8, D10, S6, S9). These findings are similar; this could be because there is consensus about grid congestion and its impact on charging infrastructure.

The literature suggests the lack of predictability of charging time and location can cause trouble when BET use goes up and logistic carriers may see this as reason not to use BETs (Govik, 2024). The results from the empirical study confirm that efficiency is very valuable to logistic carriers but that some companies can predict their arrival times very accurately while others cannot (I1, I4, D2). This could be different for each company as their service may differ, for a company that deals with mail for example the accuracy of estimated time of arrival is of importance (I4). This shows companies should be able to accurately estimate their time of arrival and this would help overcome the planning obstacle.

Research by Govik in 2024 proposes a lack of digital infrastructure where traffic data, data from carriers and of CPOs are combined (Govik, 2024). The need for an advanced booking system for public chargers is also emphasized in the empirical study (D2, D6, D9, D10, S6). A difference found in the empirical study is the fact that new trucks are often integrated in the Internet of Things and will therefore be able to interact with the booking system (I5). It is possible that this is not found in the literature study because the system does not exist yet and the exact capabilities and requirements are not yet defined. The integration of the truck within the booking system could have potential in making the system more accurate and smarter.

From the literature study it was found that CPOs need to arrange cybersecurity measures as an attack could lead to downtime (Pawlak, 2025). In the empirical study the need for a robust charging system is found (I1, D9). Another thing found is that CPOs not only choose MCS because of speed but also because of reliability (I5). The need for cybersecurity did not come out the empirical study. A reason for this could be that cybersecurity is seen as standard by CPOs and therefore it has not been emphasized. This does not mean CPOs should not take cybersecurity into account when building their digital infrastructure.

The solutions to deal with grid capacity shortage proposed by the literature are the addition of battery energy storage systems (BESS) and the use of renewable energy sources (RES) generated directly at the charging site (Moorthy et al., 2022; Mulder, 2014; Stith et al., 2025; Zuo & Li, 2024). From the empirical study it was found BESS is crucial when charging at megawatt power levels (I2, I3, D1, D8, S8, S11). Also, other innovative ideas like cable pooling are suggested (I3). The quantitative study suggested the addition of RES at the charging site has a large impact on the NPV of charging sites. The differences in findings are that cable pooling has not been suggested by literature and RES is not seen as necessary for dealing with grid capacity issues but more as a financial choice. The reason this differs may be because cable pooling is a relatively new idea and not yet possible in every county in the EU.

### *Financial aspects*

The literature review found the financial obstacle that the costs of grid connections vary per country and are based on the peak power use (Hildermeier & Jahn, 2024; Verbeek et al., 2025). In the empirical study it was found that the grid connection cost structure creates financial hurdles because it is based on the peak power use (I3, D1). This confirms the cost structure found in the literature review but does not mention the difference per country. This could be because while there are differences per country, it is a financial obstacle in all of EU.

Research by Otteny et al. in 2024 suggests the high capital expenditure of charging sites causes the need for high utilization to become profitable. The empirical research uncovered that utilization is currently too low to become profitable (D9, S6). It also revealed that an energy utilization rate of 20% within the next 10 years is necessary for financial feasibility (D2, CIBCAT analysis). The difference is that the empirical study suggests a utilization rate percentage while the literature only suggests a 'high' rate. This could be because companies were the source for the empirical study and these organizations must define goals, also the quantitative analysis is based on three-year breakeven time, and this is in line with business decisions.

The need for policy measures in favour of battery electric trucks was emphasized in the literature, suggesting lower toll fare in combination with the incentivising of a dense MCS network (Jahangir Samet et al., 2024). The empirical study suggests prolongation of the existing subsidiary arrangements for both CPOs and BETs to overcome financial barriers and give assurance to CPOs to invest in future projects (I3, D2). These findings are similar as they both advocate for financial incentives to support the transition to electric long-haul trucking.

### *Policy aspects*

Research by Shoman et al. in 2023 suggests that AFIR may not be sufficient as it does not take MCS charging speeds into account while these speeds are necessary for long-haul electric trucks. The empirical study also found shat AFIR is not sufficient for long-haul electric trucks (D3, D7, S3, S13). It also found that the differences between countries in Europe are too big to draw one line for whole EU (I6, D3). This partially overlaps as both studies found the insufficiency of AFIR, but the empirical study also found the imbalance of charging needs in Europe.

The literature review found that the waiting time of 5 to 8 years to get a grid connection is too long compared to the time to build renewable energy facilities and charging hubs (E. C. A., 2025; Roach, 2025). The empirical study found that CPOs need assurance of where a grid connection will be available to be able to invest in future projects (D2, I3, D1, D4). The similarity is that grid connections take too long but the need for assurance and transparency is only suggested in the empirical study. This could be because the companies working in the charging infrastructure system have experience first-hand what problems are caused by the grid connection waiting times.

Research by Pató et al. in 2024 found that the procedure of getting a grid connection is not efficient. The empirical results are that the process of getting a grid connection is too lengthy and needs to be streamlined D1, D2, D3, D4). The need for smart location planning of new grid connections along TEN-T by DSOs needs to be improved (D1, D2, S12). This result differs from literature as it mentions the planning of grid connections along TEN-T. The reason this differs is because the research by Pató et al. is about general grid connections and not for charging infrastructure specific.

The literature review suggests that the TCO of BETs will be lower than diesel trucks according to forecasts (Claes et al., 2022). The empirical study found that charging at public charging stations is currently too expensive compared to diesel trucks and private charging stations (I1, S1). The findings do not directly overlap but could say the same thing as most charging (80-90%) will be done at depots so the TCO of BETs could be better than diesel in the future.

## 5.2 Implications and further research

The comparison of literature and empirical results has implications on theory and practice. For digital infrastructure, a practical implication for logistic carriers is that they should work on their ability to estimate arrival times (Govik, 2024; I1, I4, D2). For theory, the exact requirements of the booking and planning system should be researched, combining IoT capabilities of trucks with other data sources (Govik, 2024; I5; D2, D6, D9, D10, S6).

The need for battery storage at the charging site is evident (Moorthy et al., 2022; Mulder, 2014; Stith et al., 2025; Zuo & Li, 2024; I2, I3, D1, D8, S8, S11), but choosing for renewable energy at the charging site is a business case choice, not a grid congestion solution. The implication for this is that it may need to be chosen for each charging site depending on environment and other factors. Further research on this topic could be on the optimal battery capacity for efficiency and cost effectiveness.

The chicken-and-egg problem found in the literature and empirical study causes the need for measures by governments in EU. This would be prolongation of the current financial incentives stimulating BETs and charging infrastructure (Jahangir Samet et al., 2024; I3, D2). It is also important assurances are given that this will go on for the next years so investments can be made.

The insufficiency of AFIR implies a new version should be written implementing MCS charging speeds and taking into account the differences between countries (Shoman et al., 2023; D3, D7, S3, S13, I6). Further research should be done on what factors should be used to differentiate countries and regions to distinguish these regions.

The streamlining of procedures and prioritization of grid connections along TEN-T are the implications that can be drawn from the discussion (Pató et al., 2024; D1, D2, D3, D4; S12). Research on how this should be done and if it is possible to standardise procedures in all of Europe could be valuable.

## 5.3 Validity and limitations

The strength of this literature review lies in the actuality of the sources. Most used articles are from 2023, 2024, and 2025 (e.g., *Speth & Plötz, 2024*). Because the technology for Megawatt Charging Systems (MCS) is developing very fast, older sources would not be accurate anymore. Another strong point is the triangulation, the study does not only look at technological issues, but also at financial factors, policy and regulations. This gives a complete picture of the situation. Also, by using the Multi-Level Perspective, the findings are connected to a theoretical framework fit for studying influencing factors within an ecosystem like truck charging infrastructure.

However, there are some limitations to this research. Because MCS is a very new technology, there is almost no data from real-life situations. Most studies rely on simulations and models instead of actual large-scale testing. We do not know for sure if the technology will work exactly as predicted when thousands of trucks use it every day.

Many studies used as foundation for this project focus on specific countries like Germany and the Netherlands. The situation regarding grid capacity and tax rules might be different in other European countries. Therefore, the results cannot simply be applied to the whole of Europe without caution.

# 6 Conclusion

The large-scale implementation of Megawatt Charging Systems (MCS) is currently facing obstacles resulting from combination of grid constraints, financial factors, and insufficient policy.

The most critical technical obstacle is the high volatility and peak power demand of MCS. Current grid capacity is insufficient to handle this. This issue is supported by policy inefficiencies, such as long waiting times for grid connections and a lack of prioritization for grid expansion along the TEN-T network. Furthermore, the AFIR regulation does not fully align with reality, as it ignores the necessary MCS charging speeds and misses the differences between European countries.

From a financial perspective, Charge Point Operators (CPOs) face a difficult business case in the initial phase. The current structure of grid connection costs is based on peak power use, and not to the actual energy volume used. Additionally, the "chicken-and-egg" problem - where carriers wait for infrastructure before using BETs - leads to low utilization rates in the next years, making initial investments risky.

The last technical issue is the lack of digital infrastructure for planning and booking charging slots, which is necessary as carriers rely on efficiency.

To overcome these obstacles, the following suggestions are found:

**Technical:** The addition of Battery Energy Storage Systems (BESS) to charging hubs is non-optional to deal with grid capacity issues.

**Digital:** Digital infrastructure must be developed using Internet of Things integration to allow logistic carriers and CPOs to efficiently plan charging slots.

**Strategic & Financial:** Adding renewable energy sources is a good option for financial feasibility. Finally, DSOs need to plan grid expansions along the TEN-T network, and prolongated subsidies are essential to bridge the difficult initial phase. It is important CPOs are assured of financial support in the future and transparency is needed about the grid capacity and planned extensions.

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## 7.1 AI use declaration

During this research project, I have made use of generative AI, specifically Gemini pro. I have used AI as an inspiration source using prompts like: *What other topics could be interesting to investigate for this research question?*
Doing so made my research more complete because I was able to identify more obstacles because of the extra directions AI have me. I have not used any sources found by AI but have only used these directions to find my own sources using google scholar.

I have also used Gemini to make search strings for google scholar by asking prompts like: *Make a search string for google scholar to find sources about obstacles for MCS specifically for charge point operators.* The search strings I got from Gemini were the following:

("megawatt charging system" OR "MCS" OR "high power charging") AND ("charging point operator" OR "CPO" OR "infrastructure operator" OR "charge point operator business model”) AND ("barriers" OR "obstacles" OR "challenges" OR "risks”) AND ("heavy duty vehicles" OR "electric trucks" OR "freight transport")

This has saved me a lot of time as writing these yourself is a lengthy process which can be outsourced to AI easily.
I have not asked Gemini to write any text and wrote all of the text myself. I have also made sure to never include any names of my interviewees or other personal information in my prompts.

# Appendix A. Personal communication

9 September – Meeting with Rishab and Jorden from Cenex about the progress in this project

Discussed my research and concluded I need to look at MCS from a single perspective. Chose CPO perspective. Also gave me some directions on what obstacles to look for.

28 October – Meeting with Rishab about the use of CIBCAT, Rishab claimed the CAPEX of an MCS charger is around 350.000 euros. Also concluded the lease model would be best for evaluating the added business case of MCS as the costs of land are already paid because CCS chargers already cover the terrain and no extra land is needed.

12 November – Meeting with Rishab and Jorden about project progress. Came to the aim of CIBCAT analysis, the aim is to find the utilization rates necessary for breakeven in 3 years because this is what most companies aim for.

# Appendix B. Symposium Notes

Data is available upon request, in compliance with GDPR regulations.

# Appendix C. Interview transcripts

Data is available upon request, in compliance with GDPR regulations.

# Appendix D. Documentation

| Label | Organization | Title | Key findings |
|---|---|---|---|
| D1 | Milence | Future-Proofing Europe's Grid for Electric Heavy-Duty Vehicles | Milence grid connections range from 6 to 30 MW. Energy storage and management systems needed for efficiency and reliability. Uptime and reliability will be imporant for the adoption. Milence seems to already have the data management and software inntergration under control. Safety very important and can be achieved by smart site design. Most EU countries lack efficient processes to verify available grid capacity. Because of this a lot of effort goes into applications from both the CPO as the DSO side while most of the grid connections turn out not suitable. More transparancy necessary on the wating time and place on waiting list. Investments by DSOs along TEN-T Network are necessary as these project take time and will be used. Renewable energy should be directly connected to the charging sites, this could be made easier by removing legal barriers. Grid fees are structured based on annual peak demand, which increases costs compared to volumetric fees. A different structure could enhance the adoption of electric HDVs. |
| D2 | Milence | The readiness of public charging infrastructure for electric long-haul trucks | Current charging capacity in EU is enough to support the current fleet in some countries. 15%, 20% and 25% of energy utilization rates are seen as possible. Misalignment between localization of truck use and charging capacity is a problem. A dense anough network along TEN-t is not there yet. Share of MCS chargers taken into account are 25%, 50% and 75%. MCS provides a lot of benefits with land use and charging speeds but this can only happen with efficient booking and planning systems. Financial barriers have to be adressed by keeping subsidies going and making sure grid connection uncertainties go away. Policy recommendations: Accelerating the grid connection processes along TEN-T is essential, AFIR backed hubs need to be labeled critical infrastructure to overcome administrative delays, guarantees by EU to give certainty to CPOs, subsidies expanded and kept, BET TCO has to be lowered using policy measures. |
| D3 | ICCT | Charging infrastructure needs for battery electric trucks in the European Union by 2030 | 70% of charging needs EU will be in Germany, Poland, France, Spain and Italy. Megawatt chargers will deliver almost 15% of power but only 2% of the number chargers will be delivering this power. When batteries get bigger, the need for MW chargers can be reduced by 40%. AFIR is expected to cover 50% to 70% of public charging needs. AFIR is not enough for some member states as traffic is not evenly distributed across all of EU. Policy reccomendations: Promote initiatives that focus on the deployment of HDV-specific charging infrastructure across key transport corridors in the EU. Accelerate and streamline the charging infrastructure deployment and grid permitting processes. |

| | | | |
|---|---|---|---|
| | | | Empower grid operators to make anticipatory investments. Promote transparency in grid hosting capacities and streamline the type and format of reported data. |
| D4 | Energy Transitions Commission | Building grids faster: the backbone of the energy transition | 1. Implement a strategic vision for grids and generation coordinated across key stakeholders and supported by clear data.<br>2. Address slow permitting and approvals and grow societal acceptance.<br>3. Address skill, component and material gaps.<br>4. Reform financing structures and increase access to finance. |
| D5 | EATON | Revolutionizing Commercial EVs: Megawatt Charging and Its Implications | Thermal management necessary for megawatt charging. |
| D6 | CharIN | White Paper of Charging Interface Initiative e.V. Charging Site Recommendations for CCS and MCS for commercial vehicles | Modular design of charging sites provides flexibility and also scalability (transitioning from CCS to MCS and future automation). The difference in traffic and regulations between regions has a lot of impact on the design of a charging site. Volatility of public charging infrastructure causes the need for high peak loads. To facilitate this, BESS is needed to stabilize the grid load and use peak shaving. The need for an efficient planning and booking system is emphasized. |
| D7 | European Union | REGULATION (EU) 2023/1804 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 September 2023 on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU | Acceleration of public charging for E-HDVs necessary. Along TEN-T public charging per distance, and in industrial areas the possibility for overnight charging. Goal for 2030 is 3600 kW per charging site and one site per 60 km in core. 1500kW per 100 km in comprehensive TEN-T. No mentioning of MCS, 350 kW chargers only mentioned. |
| D8 | New Energy Coalition | Van congestie naar vermogen Collectieve en praktijkgerichte oplossingen voor de aanpak van netcongestie | Oversight needed to find places where there is capacity for gird connections. The sharing of connections could also be useful, when a company has a day profile and another company has a night profile they could share the high price of peak use. Addition of BESS is mentioned as solution. |

| | | | |
|---|---|---|---|
| D9 | TNO | Executive summary Living Lab Heavy duty Laadpleinen | Current use is too low for profitability within 10 years, need for higher utilization rate to compete with depot charging prices. TCO of BETs is currently too high but with more long haul BETs on the road this will become competitive with DTs. The reliability of chargers has to be very high because they are down for a long time when broken. A well organized service system would improve this. |
| D10 | TNO | Reccomendations per stakeholder Living Lab Heavy duty Laadpleinen | Minimum of 400 kW per charger recommended. Clear visualization of price per kWh needed. Service center has to be easy to contact. For planning it is recommended to take a 15% lower charging speed than the actual maximum of the charger. Use booking systems and try to avoid peaks between 12:00 and 17:00. Above 1,75-2 MW the grid connection gets substantially more expensive. The recommendation for policymakers is to change the way of connection pricing. |

## Appendix E. Reasoning for quantitative analysis

Chosen for own and operate model with zero land cost because for this project the only incremental change of adding an MCS charger to your charging site is relevant. It is assumed that the land costs are already paid for because the charging hub already exists.

Communication costs can also be neglected as the internet connectivity for the charging site should already be there for CCS chargers.

Maintenance costs are put at 7500 euro per year because the costs of CCS2 chargers are up to 3000 dollars per year and the price of an MCS charger is approximately 3 times higher than CCS2 (Lee & Clark, 2018).

Payment system subscription fees are neglected as well as this is an insignificant number.

Day profile is chosen as MCS will mostly be used during the day.

Companies aim for a breakeven time of a project of three years so the utilization rate necessary to get this will be researched. In Milence whitepaper a variety from 15% to 25% is discussed so a combination of these utilization rates will be used. It is assumed the utilization rate will grow in the next years so a rising timeline will be used.

# Appendix F. Realised research plan

In this project all the contents of the research plan have been realised. The timing was a little different than planned, with the interviews not being performed in the same phase but rather spread out through the empirical study phase. This meant the CPO interview was done after the results of the interviews with logistic carriers and policymakers were analysed. This was the result of problems with getting in touch with CPO employees and them being busy. Another small difference is that the data used for the quantitative analysis came from reasoning and conversations with Rishab (found in appendix A), and not from the interviews with CPOs. The CPOs did not want to disclose information as it was confidential, and it also turned out this information was not necessary. In figure 11 the realised research plan (which is almost identical to the original plan) is shown.

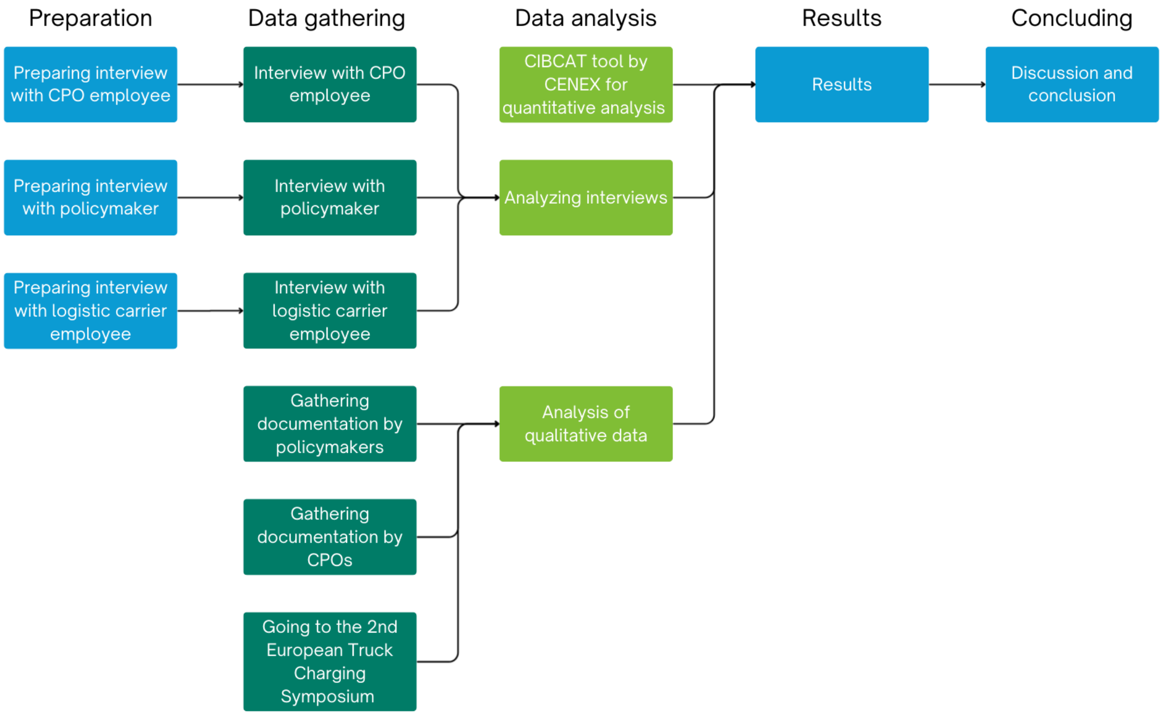


*Figure 11 Realised research plan*

## Appendix G. Discussion scheme

| Answers literature review | Answers empirical study | Similarities (=) | Differences (≠) | Explanation |
|---|---|---|---|---|
| High power demand of 979 kW optimal for charging during mandatory break (Schneider et al., 2023) Concentrated charging demand at middle of the day (Speth & Plötz, 2024) Volatile energy use curves complicates situation for grid managers (Stith et al., 2025) Insufficient capacity for high power grid connections (Burges et al., 2021) | Grid connections are not always suitable for multi megawatt power. (D1) Peak power use is too high for grid connections. (D1) Grid congestion is largest technical obstacle to implementation of MCS (I2, I3, I5, I6, D1, D3, D8, D10, S6, S9) | Volatility and high peaks cause problems with grid connections<br><br>Grid congestion forms obstacle to implementation of MCS | | This is a large topic in energy infrastructure at this time |
| Bad predictability of charging needs leads to uncertainty for logistic carriers (Govik, 2024) | Efficiency very valuable to carriers (I1, I4, D2). Charging needs can be predicted accurately at some carriers (I4) | Uncertainty can be a problem for logistic carriers as they value efficiency | Charging needs could be predicted accurately at some carriers | Differences between logistic carriers' business model cause differences in planning |
| Lack of digital infrastructure to integrate traffic data and data from carrier and CPO (Govik, 2024) | Advanced booking system necessary with integration of truck in IoT (D2, D6, D9, D10, S6, I5) | Emphasis on the need for a booking system | The addition of IoT use with trucks connecting to the system | System does not exist yet, so exact capabilities are not yet defined |
| Need for cybersecurity measures to prevent outage (Pawlak, 2025) | Reliability and uptime are vital for logistic carriers (I1, D9). MCS is more reliable than CCS (I5) | Robust charging systems needed | Reliability and uptime are emphasised but not cybersecurity | |
| Battery energy storage systems and the addition of renewable energy sources is needed to combat grid issues (Stith et al., 2025) (Moorthy et al., 2022) (Mulder, 2014) (Zuo & Li, 2024) | BESS is crucial when charging at megawatt power (I2, I3, D1, D8, S8, S11) Other innovative ideas like cable pooling can battle grid congestion (I3) CIBCAT suggests RES make financial sense | Battery storage is crucial for megawatt charging | Literature emphasised RES but this is not a big thing in practice Other solutions like cable pooling are suggested in empirical research | The use of renewable energy is somewhat implied but does not mean it has to be directly at the charging site though it can be very profitable and cable pooling relies on local regulation |

| | | | | |
|---|---|---|---|---|
| Costs of grid connection vary per country and are based on peak power use (Hildermeier & Jahn, 2024) (Verbeek et al., 2025) | The cost structure of grid connections creates financial problems as peak use is expensive (I3, D1) | Cost structure creates problems at high peak loads | Empirical research suggest this is a problem in all of EU and not per country | While there are differences per country this could be a problem in all EU countries |
| High CAPEX causes need for high utilization rate (Otteny et al., 2024) | Utilization rate is currently too low to become profitable (D9, S6) Utilization of 20% within 10 years is needed (CIBCAT analysis) (D2) | High utilization rate necessary | 20% not found in literature | The empirical data was gathered from companies, so these sources mention clearer goals |
| Need for policy measures in favour of BETs. Toll fare needs to be low and a dense network with MW charging capacity (Jahangir Samet et al., 2024) | Prolongation of subsidiary arrangements for both CPOs and BETs necessary to overcome financial barriers in the future (I3, D2) | The need for financial incentives during the initial phase of electric trucking | | |
| AFIR may not be sufficient as it doesn't take MCS power into account while this is necessary for long haul trucking (Shoman et al., 2023) | AFIR is not considered sufficient for long haul electric trucking (D3, D7, S3, S13) Differences between countries are too big to draw one line for whole EU (I6, D3) | AFIR not sufficient as MCS is not taken into account | Differences between countries and need for charging infrastructure | The businesses experience the differences between countries first hand |
| Waiting time of 5 to 8 years for a grid connection too long compared to time it takes to build renewable energy facilities and charging hubs (Roach, 2025) (E. C. A., 2025) | CPOs need more assurance to be able invest in future projects (D2, I3) Transparency needed in grid capacity for CPOs to plan and invest (D1, D4) | Grid expansion takes too long | CPOs need assurance for future and more transparency to make investments | The practical knowledge and experience by CPOs is not easy to find in academic research |
| Procedure to get a grid connection is inefficient (Pató et al., 2024) | Process of getting a grid connection is currently too long and needs to be streamlined (D1, D2, D3, D4) Smart location planning related to TEN-T needs to be better (D1, D2, S12) | Inefficiency of grid connection procedure | Smart location planning along TEN-T | Literature is more general and not just for BET charging and therefore does not mention TEN-T |
| TCO of BETs expected to be lower than diesel in forecasts (Claes et al., 2022) | Charging at public charging stations is currently too expensive compared to private charging and diesel trucks (I1, S1) | | TCO of BET lower than diesel in future but public charging is too expensive | This could be because most charging will be done at depots and this could be financially feasible |