Charging Infrastructure Choices for Zero-Emission Freight: A Stakeholder-Centric Assessment Using MAMCA

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Charging Infrastructure Choices for Zero-Emission Freight: A Stakeholder-Centric Assessment Using MAMCA

By

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Preface

This thesis marks the culmination of my Master of Science journey in the Management of Technology program at Delft University of Technology. While starting the studies during the first autumn of COVID pandemic was quite challenging, it also provided a unique opportunity to focus deeply on learning and personal development. Despite the unusual start, the past years have been immensely rewarding.

First of all, I would like to thank Jan Anne Annema, Lóri Tavasszy, and Nazli Aydin who helped me to shape and focus my final thesis. From the first ideation with Lóri until the last refinement with Jan Anne, their guidance, critical feedback, and continuous support have been instrumental in shaping both the direction and quality of this work. I also extend my thanks to the faculty and staff at both TU Delft and TU Munich for creating a learning environment that was not only intellectually stimulating but also genuinely enjoyable.

I also want to thank all of the interview participants who generously dedicated their time and expertise to make this research insightful. Their perspectives were invaluable in shaping the stakeholder analysis and bringing real-world relevance to the study. Finally, I want to thank my partner, Veronika, for her support and encouragement, especially during the final stretch of this journey.

Benediktas Opeikis
Berlin, June 2025

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Executive summary

This thesis compares the adoption potential of Battery Electric Heavy-Duty Vehicles (BEHDVs) using static charging and Electric Road Systems (ERS) enabling dynamic charging. Using the Multi-Actor Multi-Criteria Analysis (MAMCA) supported by the Best-Worst Method (BWM), the study evaluates both pathways from the perspectives of six key stakeholders in the European road freight sector: carriers, shippers, vehicle manufacturers, electrical grid operators, road operators, and freight forwarders.

Stakeholder-specific criteria were identified through eleven semi-structured interviews with senior experts from industry-leading organisations, ensuring that the analysis reflects practical, high-level decision-making perspectives. These criteria, covering economic, operational, societal, and environmental dimensions, were weighted using the BWM and linked to measurable performance indicators. Data were normalised to a common scale, enabling comparison between scenarios according to stakeholder priorities.

The results reveal a diverse preference landscape. Vehicle manufacturers and freight forwarders show a clear inclination towards the BEHDV-only pathway, citing higher technological maturity, operational flexibility, and readiness for near-term deployment. Grid and road operators strongly favour BEHDV + ERS, valuing its potential to distribute electricity demand more evenly, reduce peak loads, and significantly improve land use efficiency compared to large-scale static charging hubs. Shippers and carriers express moderate ERS preference, primarily linked to potential gains in driver well-being and delivery reliability. Although these depend on extensive corridor coverage and high utilisation rates.

Thematic analysis shows operational and technical performance as the most influential driver in both pathways, followed by economic considerations, which gain more prominence in the ERS scenario due to its potential infrastructure-efficiency advantages. Societal and environmental considerations, while lower in stakeholder weightings, remain strategically relevant for long-term policy alignment. Sensitivity analysis identifies TCO for carriers and infrastructure investment requirements for road operators as the most impactful levers for shifting preferences. Targeted subsidies, utilisation-based ERS pricing, and co-financing mechanisms could make ERS more competitive, while space constraints in dense freight corridors could further tilt the balance in its favour.

The findings indicate that no single pathway fully satisfies all stakeholder priorities. A phased, complementary approach is recommended: near-term deployment of BEHDV-only solutions using mature static charging to accelerate electrification, coupled with targeted ERS rollout along high-utilisation corridors to capture long-term grid, land use, and operational efficiency benefits. Harmonised technical standards, supportive regulatory frameworks, and ERS-ready vehicle designs will be critical to ensure interoperability in the transition to zero-emission long-haul freight.

Nomenclature

Abbreviations

Abbreviation	Definition
ACEA	European Automobile Manufacturers' Association
AFIR	Alternative Fuels Infrastructure Regulation
BEHDV	Battery Electric Heavy-Duty Vehicle
BEV	Battery Electric Vehicle
BWM	Best-Worst Method
CapEx	Capital Expenditure
CCS	Combined Charging System
CI	Consistency Index
CPO	Charge Point Operator
CSI	Cost Stability Index
CV	Coefficient of Variation
EC	European Commission
ERS	Electric Road Systems
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
ICE	Internal Combustion Engine
IRI	Infrastructure Readiness Index
LCV	Light Commercial Vehicle
LUI	Land Use Intensity
MAMCA	Multi-Actor Multi-Criteria Analysis
MCS	Megawatt Charging System
OEM	Original Equipment Manufacturer
OpEx	Operational Expenditure
R&D	Research and Development
ROI	Return on Investment
SD	Standard Deviation
SME	Small and Medium-sized Enterprise
TCO	Total Cost of Ownership
TRL	Technology Readiness Level
tkm	Tonne-kilometre
ξ (xi)	Consistency Ratio

1 Introduction

1.1 Motivation

The road freight sector faces urgent decarbonisation pressure as part of broader climate commitments. The European Commission's ambition for Europe to become the first climate-neutral continent by 2050 demands rapid emission reductions from high-impact sectors, with road transport, responsible for 760 million tonnes of CO_2 in the EU in 2022 a primary target (European Commission, 2019; Destatis, 2024). Heavy-duty road freight is particularly challenging, as its operational demands make low-emission transitions more complex than in passenger transport. Multiple low- and zero-emission propulsion systems are under development, including fuel cell electric vehicles (FCEVs), battery electric vehicles (BEVs), and advanced biofuels (Kluschke et al., 2019). Among these, BEVs have emerged as a leading candidate for achieving large-scale zero tailpipe emissions, due to high energy efficiency and maturing battery technologies (Rogstadius et al., 2024). However, for long-haul freight, battery electric heavy-duty vehicles (BEHDVs) face significant operational barriers, including range limitations, charging times, payload constraints, and unfavourable total cost of ownership compared to diesel (Gillström, 2024).

Electric Road Systems (ERS), infrastructure enabling in-motion charging, are proposed as a complementary solution to static charging. ERS could reduce battery size requirements, improve energy efficiency, and increase vehicle utilisation, potentially addressing several BEHDV limitations (Deshpande et al., 2023). While static charging offers near-term feasibility, ERS presents long-term efficiency benefits, making their comparative assessment critical for shaping effective decarbonisation strategies. The core decision is how to allocate limited public and private investment between static and dynamic charging to maximise near-term feasibility while preserving long-term system efficiency.

This study focuses explicitly on EU long-haul freight BEHDVs. In this context, static charging refers to depot or overnight charging as well as public high-power charging and megawatt charging systems (MCS). ERS includes overhead, conductive ground, and inductive charging technologies, but for the purpose of quantification in this thesis, performance indicators are based on overhead ERS systems unless otherwise stated.

1.2 Research gap

The literature offers rich analyses on BEHDV technology, charging concepts, and ERS pilots, but it rarely compares static charging and dynamic charging as competing (and potentially complementary) transition pathways for heavy-duty road freight. Moreover, studies often optimise technical performance while under-representing the heterogeneous priorities of the decision-makers who determine adoption. This thesis addresses that gap with a stakeholder-centred, comparative assessment of BEHDV-only versus BEHDV+ERS deployment.

1.3 Research objectives

The objective of this thesis is to evaluate how integrating ERS alongside BEHDVs enhances stakeholder value and operational feasibility in the transition to sustainable freight transport. This is achieved through a direct, stakeholder-informed comparison of BEHDV adoption with and without ERS using a consistent methodological framework.

1.4 Research questions

Main research question: *To what extent does the integration of Electric Road Systems (ERS) alongside Battery Electric Heavy-Duty Vehicles (BEHDVs) enhance stakeholder value and operational feasibility in the transition to sustainable freight transport*?

To answer the main research question, the secondary research questions were formulated:

1. *Who are the decision maker stakeholders that are involved in the adoption of BEHDVs and ERS?*
2. *What evaluation criteria do key these stakeholders use to assess the adoption of BEHDVs with and without ERS?*
3. *What is the relative importance of the identified evaluation criteria for each stakeholder in the context of BEHDV adoption with and without ERS?*
4. *How do the adoption options of BEHDVs with and without ERS perform when evaluated against stakeholder-specific criteria and priorities?*

1.5 Research approach

This thesis applies the Multi-Actor Multi-Criteria Analysis (MAMCA) framework, supported by the Best-Worst Method (BWM) for stakeholder-specific criteria weighting. MAMCA is particularly well-suited to contexts where decisions must integrate diverse priorities and trade-offs. The research combines qualitative interviews to identify criteria, quantitative BWM surveys to assign weights, and performance indicators to evaluate each scenario. Performance indicators refer to measurable metrics for each criterion. Normalisation refers to the process of adjusting these metrics to a comparable scale. A weighted score is calculated by multiplying each criterion's normalised indicator score by its assigned stakeholder-specific weight. The results are reported at two levels: stakeholder-level preferences, and thematic aggregation into economic, operational/technical, and societal/environmental categories, enabling a clearer interpretation of cross-stakeholder trends..

1.6 Contributions

This thesis advances knowledge and practice by:

- Filling a critical research gap through a direct, stakeholder-informed comparison of static and dynamic charging adoption pathways for BEHDVs.
- Extending the application of MAMCA to the freight electrification context, incorporating BWM-derived weights and performance indicators.
- Demonstrating how differences in stakeholder priorities translate into different technology preferences and adoption feasibility.
- Providing a decision-support framework for policymakers, infrastructure planners, and industry stakeholders to guide context-specific electrification strategies.

1.7 Thesis structure

The remainder of this thesis is structured as follows:

- **Chapter 2 - Literature Review:** Reviews the current state of BEHDVs, static charging, and ERS, including technological developments, implementation challenges, and research gaps.
- **Chapter 3 - Methodology:** Describes the MAMCA framework, data collection and analysis process, and the use of the BWM for stakeholder-specific criteria weighting.
- **Chapter 4 - Results:** Presents the identified stakeholders, their criteria, thematic grouping, weightings, cross-criteria analysis, measurable indicators, a synthesis of weights and performance indicators, normalisation and stakeholder-weighted scenario evaluation, sensitivity analysis, and a summary of findings.
- **Chapter 5 - Discussion:** Interprets the results through key findings, explores implementation considerations, highlights strengths and limitations, and offers recommendations for policy and practice.
- **Chapter 6 - Conclusion:** Summarises the main findings, explicitly answers the research questions, emphasises the research contributions, and suggests directions for further study.

2 Literature review

2.1 Literature Review Methodology

The aim of this literature review is to critically examine and synthesize existing research on the decarbonization of road freight transport, with a particular focus on the comparative evaluation of BEHDVs and ERS. The goal is to identify technological, operational, infrastructural, environmental, and socio-political dimensions relevant to these decarbonization strategies, as well as to detect gaps in the literature that justify the need for a stakeholder-centric assessment.

To ensure a comprehensive and systematic coverage of relevant academic and industry research, a structured search strategy was employed. Databases including ScienceDirect, Web of Science, and Google Scholar were used for academic literature, while industry reports and working papers were identified through platforms such as ResearchGate, institutional repositories, and government portals (e.g., European Commission publications).

The initial search used a predefined list of key terms representing the technologies under investigation, including “battery electric trucks,” “heavy-duty electric vehicles,” and “electric road systems.” As relevant publications were reviewed, the search vocabulary was expanded to include additional terms found in titles, abstracts, and bibliographies, such as “catenary infrastructure,” “dynamic electric roads,” and “stationary depot charging.” This approach allowed the identification of both core and related studies. Each publication was screened for relevance and assigned to one of three thematic categories:

1. Studies analysing ERS-specific systems and deployment,
2. Studies on BEHDVs using conventional charging infrastructure,
3. Broader analyses relevant to freight decarbonization or transition planning.

Inclusion criteria were defined to retain studies that:

1. Provided empirical data, simulation-based evidence, or systematic conceptual analysis related to BEHDVs and/or ERS,
2. Addressed at least one of the identified thematic dimensions (technical, economic, environmental, or social), and
3. Were published in peer-reviewed journals, recognized conference proceedings, or issued by authoritative public or industry bodies.

Studies were excluded if they lacked methodological transparency, were purely speculative, or focused on passenger rather than freight applications.

Following initial screening, full-text analysis was conducted to categorize insights into thematic clusters, which subsequently informed both the evaluation criteria and the stakeholder mapping process. This approach ensured that the literature review not only reflected the state of knowledge but also directly supported the design and implementation of the stakeholder-driven MAMCA framework employed in this thesis.

2.2 Current Status of Road Freight Transportation

In 2024 according to ACEA (2025a; 2024), diesel trucks remained the dominant choice for buyers in the European Union, accounting for 95.1% of total new registrations (down from 95.7% in 2023). Despite considerable growth last year, electrically chargeable vehicles still made up only 2.3% of the EU truck market.

Diesel Trucks

Diesel-powered trucks are the predominant mode of freight transportation in the EU, accounting for 77.8% of total freight traffic in 2022. Despite their critical role in goods movement, the diesel truck sector faces growing challenges related to environmental impact and the need for decarbonisation (CAE & GCEE, 2025).

First, diesel fuel prices are subject to market volatility, leading to unpredictable operating costs and additional risk. As can be seen in the DKV (2025) data, diesel prices can fluctuate up to ±10% month-on-month basis in European countries. As fuel accounts for 27-30% of the road transportation price, such fluctuations can have a significant dent to the profitability in this low-margin industry (Gonon, 2025). In addition to that, the biggest crude oil exporters in the world tend to have questionable human right practices or be actively hostile to other countries (OEC, 2025).

More importantly, heavy-duty trucks and buses are significant contributors to air pollution and greenhouse gas emissions, emitting over 205 million tonnes of CO_2 in 2022 (Destatis, 2024). Heavy-duty vehicles account for a large portion of global CO_2 emissions, NO_X, and particulate matter, which are harmful to both human health and the environment (Reşitoğlu et al. 2014). The European Parliament (2024) has set stringent CO_2 emission reduction targets for trucks, prompting the logistics industry to seek cleaner alternatives.

These challenges underscore the need for the freight transportation industry to explore and adopt more sustainable and cost-effective alternatives to diesel-powered trucks.

Battery Electric Trucks

Similarly, as electric cars have emerged as an alternative to the diesel cars, battery electric trucks have a potential to disrupt the logistics industry. First, it is important to note that BEVs produce zero tailpipe emissions, reducing air pollutants and GHGs (Li et al, 2022). However, it's important to consider the full life cycle of these vehicles. A study by Zhang et al (2023) indicates that the environmental impact of BEVs is influenced by the energy sources used for electricity generation; non-renewable energy sources can diminish the environmental benefits of BEVs.

Moreover, although BEHDVs typically have higher upfront costs, their operational expenses can be quite lower than diesel trucks. BEHDVs have reduced fuel costs, especially when electricity pricing is stable or favourable, and benefit from lower maintenance requirements due to fewer moving parts in the electric drivetrain (Samet et al., 2024, Bhardwaj & Mostofi, 2022). Additionally, the opportunity costs associated with charging downtime, such as driver wages and potential lost revenue during charging periods, must be factored into operational cost analyses. A sensitivity analysis of the levelized cost of driving highlights key factors influencing operational cost competitiveness, including battery pack price, charging power availability, and the operational driving range. The study by Samet et al. (2024) suggests that for certain operational profiles, especially urban logistics, battery electric trucks can already be economically competitive without additional policy incentives. However, for heavier trucks and longer trips, strategic infrastructure investments, such as high-power charging stations, are crucial to ensuring cost-competitiveness.

Furthermore, recent technological progress continues to significantly boost the feasibility of BEHDVs, particularly through improvements in battery energy density and cost. According to Link et al. (2024), system-level battery costs have declined rapidly, dropping from approximately 275 EUR/kWh in 2020 (near-market estimate) to projections of around 140 EUR/kWh by 2030 and potentially 70 EUR/kWh by 2050. These trends reflect an annual cost reduction rate of about 6.5% in the 2020-2030 period (Link et al., 2024).

In parallel, battery performance has improved tremendously. König et al. (2021) report that volumetric energy density at the battery pack level for existing battery electric vehicles ranged from approximately 300 to 550 Wh/L in 2020, depending on cell format and integration efficiency. With continued innovations in battery design, such as cell-to-pack strategies and improved thermal management, projections suggest that volumetric energy densities could reach up to 1000 Wh/L by 2030. These advances allow for higher energy storage within the same physical volume, thereby supporting longer ranges for heavy-duty electric trucks without increasing battery size or vehicle weight.

Beyond performance, battery cost remains a crucial enabler. While earlier studies cited battery costs around 1100 USD/kWh in 2010, they had already fallen by 89% to 137 USD/kWh by 2020 (Bhardwaj & Mostofi, 2022). More recent meta-forecasting now projects battery system prices falling below 140 EUR/kWh by the early 2030s, with 100 EUR/kWh being a plausible threshold by the 2050s (Link et al., 2024). Such levels are considered a tipping point for cost parity with diesel trucks, even without substantial policy incentives. These improvements in cost and performance substantially enhance the operational and economic viability especially of BEHDVs. By reducing total cost of ownership (TCO) and overcoming prior limitations on range and charging time, these developments support accelerated market adoption in line with zero-emission transport targets.

However, there are also a few challenges that are still to be solved. One of the most critical challenges to the large-scale deployment of BEHDVs is the development of adequate charging infrastructure. BEHDVs have much higher energy demands compared to passenger or light weight BEVs, both in terms of charging power and operational coverage, which complicates infrastructure planning and investment. Shoman et al. (2023) highlight the scale of the required infrastructure: to support a 15% penetration of BETs in European long-haul freight by 2030, approximately 40000 overnight chargers (50-100 kW) and 9000 megawatt-scale chargers (0.7-1.2 MW) would be necessary. This demand reflects the need for both overnight and on route high-power charging, with each type serving different stop durations mandated by EU driving regulations. Another layer of the infrastructure challenge lies in the misalignment between vehicle adoption and infrastructure deployment. While expanding grid connections at logistics hubs and highway corridors is essential to support high-power charging, such upgrades often lag behind the pace of electric truck deployment, creating critical bottlenecks (Hacker et al., 2024). This dynamic is further complicated by what Raoofi et al. (2025) describe as a “chicken-and-egg” dilemma: limited adoption of electric trucks reduces the incentive to invest in charging infrastructure, while the lack of infrastructure, in turn, discourages carriers from transitioning their fleets.

Recent modelling from France reinforces the magnitude of the challenge: by 2035, 10000 slow and 2200 fast charging points will be needed across 519 service and rest areas, with electricity demand from BETs alone reaching up to 3.5 TWh annually and a national peak load of 1.1 GW (Enedis et al., 2024). In high-demand locations, infrastructure upgrades may require converting up to 50% of existing HDV parking to charging points, despite electric trucks representing a much smaller share of the fleet. Moreover, 630 EUR million in investment is estimated for upgrading the power grid. It is required primarily at the distribution level to accommodate this transition (Enedis et al., 2024).

Moreover, Bhardwaj and Mostofi (2022) identify additional barriers, such as the lack of standardization across charger types, commercial viability concerns, and the high upfront capital investment required for public or battery-swapping stations. These factors create uncertainty for both public and private sector investors, further slowing infrastructure expansion.

Finally, the promised reduced environmental impact of battery-electric trucks heavily depends on the electricity generation mix and grid capacity available for recharging. To realize the environmental benefits associated with BEHDVs, electricity must predominantly come from renewable or low-carbon sources. A study by Shoman et al. (2023) highlights that battery electric long-haul trucks largely increase electricity demand, particularly concentrated at public fast-charging stations. This raises concerns regarding grid stability and the environmental impact, depending largely on how the additional electricity is generated. The study emphasizes that if electricity is predominantly generated from fossil fuels, it can partially offset the environmental advantages of battery electric trucks. Therefore, it is essential to guarantee a renewable energy-dominated electricity supply for maximizing the environmental benefits of BEHDVs in freight transportation (Shoman et al., 2023).

In summary, while BEHDVs offer substantial environmental and running cost benefits, addressing infrastructure and energy supply challenges is crucial for their widespread adoption in road freight transportation.

Technological Readiness of the Battery Electric Trucks

While developments in battery performance, cost, and energy density have accelerated the commercial viability of BEVs, a distinction must be made between component-level technological maturity and full system readiness for broad deployment. Medium-duty BEVs designed for urban and regional applications have reached Technology Readiness Level 9 (TRL 9), indicating that these vehicles are not only technically validated but also integrated and operational in commercial fleets under real-world conditions (Martinez-Boggio et al., 2023).

These deployments benefit from reduced drivetrain complexity, mature battery chemistries such as NMC (Nickel Manganese Cobalt), and compatibility with overnight depot charging strategies. Vehicle models like the Volvo FL Electric demonstrate the capability to meet operational requirements for urban logistics with payloads, driving ranges, and service reliability aligned with industry expectations (Martinez-Boggio et al., 2023). As such, medium-duty BEVs are no longer experimental, they are commercially available, field-tested, and operationally competitive in their niche.

However, long-haul BEHDVs, those designed to replace diesel trucks in intercity freight transport, have not yet reached comparable levels of technological readiness. Several system-level limitations continue to delay full-scale deployment in this segment. These include the need for significantly larger battery capacities (typically 500+ kWh), which increase vehicle mass and limit payload efficiency, as well as longer and less predictable charging durations that disrupt established logistics schedules (Cheng & Lin, 2024). Even under optimized charging strategies that align with driver rest periods, each hour of operation can incur an additional 19 to 25 minutes of charging downtime (Cheng & Lin, 2024).

Moreover, real-world integration challenges persist. Expert evaluations and simulation-based analyses indicate gaps in software maturity, particularly in synchronizing charging activities with driver scheduling and route optimization tools (Roman & Zadek, 2024). These coordination challenges affect not only individual vehicle performance but also broader fleet-level logistics planning, particularly in just-in-time delivery models.

The same research has identified through industry interviews that the bottleneck in long-haul BEHDVs readiness is no longer technical feasibility but rather the lack of harmonized standards, insufficient real-world testing at scale, and unresolved trade-offs between battery mass, range, and infrastructure constraints (Roman & Zadek, 2024). As such, long-haul electric trucks remain in a transitional phase - beyond prototype, yet not fully integrated into the operational and economic logic of large-scale freight systems.

Other Charging Technologies

Two promising technologies that aim to support the adoption of BEHDVs are fast charging and battery swapping. Each has distinct technical, economic, and infrastructural implications.

Fast charging offers a practical method to recharge large-capacity truck batteries within mandated driver break periods. Charging stations with power outputs of 150 kW and above are increasingly deployed across Europe to support BEHDVs. For example, the Volvo FE can recharge a 395-kWh battery in approximately 2 hours using a 150 kW DC charger (Bhardwaj & Mostofi, 2022). Despite the longer charging times compared to battery swapping, fast charging infrastructure is relatively simpler to implement and compatible with a broader range of electric vehicle designs.

However, high-power charging requires a developed grid capacity and often necessitates costly infrastructure upgrades, particularly in urban and roadside environments (Speth & Funke, 2021, Bhardwaj & Mostofi, 2022).

Additionally, there were only around 600 chargers for BEHDVs in Europe in 2024 (Parrock, 2024) while megawatt charging capabilities were installed only in a few of them.

Battery swapping addresses the time constraints of static charging by replacing depleted batteries with fully charged units. Swapping can be completed in a matter of minutes - examples include Meyer & Meyer in Germany, where dual battery packs allow for a swap time of about 15 minutes (Bhardwaj & Mostofi, 2022). This solution is particularly suited to high-utilization fleets operating on fixed routes.

Nonetheless, adoption of battery swapping in Europe remains limited. A primary barrier is the lack of standardization across OEMs, which makes interoperability challenging and necessitates high coordination or regulatory intervention (Noto & Mostofi, 2023). OEMs currently design proprietary battery systems closely integrated with vehicle architecture and safety systems, making standardized formats politically and technically difficult to implement. Moreover, battery swapping infrastructure demands considerable capital investment to establish swapping stations and maintain a stockpile of charged batteries. Space constraints in European cities further complicate deployment (Bhardwaj & Mostofi, 2022).

A notable European pilot, RouteCharge in Germany, tested battery swapping on a 500 km corridor between Berlin and Peine. The project included three strategically located swap stations and demonstrated technical feasibility for circular logistics operations (Speth & Funke, 2021).

2.3 ERS as an Alternative Solution

ERS involves electrified roadways that provide power directly to vehicles via wireless power transfer, on-ground power supply, or overhead catenary cables. This technology enhances the performance of BEVs as it enables continuous dynamic power supply to trucks which reduces the need for large onboard batteries (Deshpande et al. 2023).

Several technology types have been proposed and tested (Figure 2.1). These primarily include overhead conductive, ground-level conductive, and inductive (wireless) systems:

1. **Overhead conductive ERS** delivers power via overhead catenary lines, which vehicles connect to using pantographs, similar to those used in rail or trolleybus applications. This technology is considered mature and technically feasible, benefiting from decades of experience in railway electrification, furthermore it can be installed without disrupting the traffic flow (Deshpande et al., 2023). According to Plötz et al. (2024), overhead line solutions face few fundamental engineering challenges, and their long-established nature implies limited need for innovation on the infrastructure side. However, the deployment of such systems involves substantial capital costs and presents aesthetic and operational constraints, such as clearance issues with bridges or tunnels and limited applicability to low-profile vehicles (Schulte & Ny, 2018).
2. **Ground-level conductive** systems supply electricity via rails embedded in or laid onto the road surface, with vehicles connecting through retractable pads. These systems offer high efficiency and can power vehicles dynamically at highway speeds. A key advantage is their minimal visual impact, but they require precise alignment and robust safety mechanisms, as the infrastructure is exposed to traffic and weather conditions such as snow and salt exposure (Jacob et al., 2023).
3. **Inductive (wireless)** charging systems transfers power via magnetic coupling between coils embedded in the road and receiver coils under the vehicle, enabling contactless energy transfer while driving. However, integrating inductive systems into road infrastructure poses measurable technical challenges, such as ensuring reliable coil embedding at shallow depths (5-10 cm), maintaining structural integrity under traffic loads, and managing heat generation during operation (Mazhoud et al., 2022). Furthermore, the efficiency of energy transfer to the vehicles is significantly smaller compared to the others ESR types - 73% vs 87% (PIARC, 2018). Thermal stress and material compatibility are additional concerns, and solutions like trench-based or prefabricated full-lane installations are being tested to address these issues. Projects like INCIT-

EV are exploring urban and inter-urban applications, aiming for scalable implementation with power levels of 30-90 kW per coil (Mazhoud et al., 2022; Schulte & Ny, 2018).

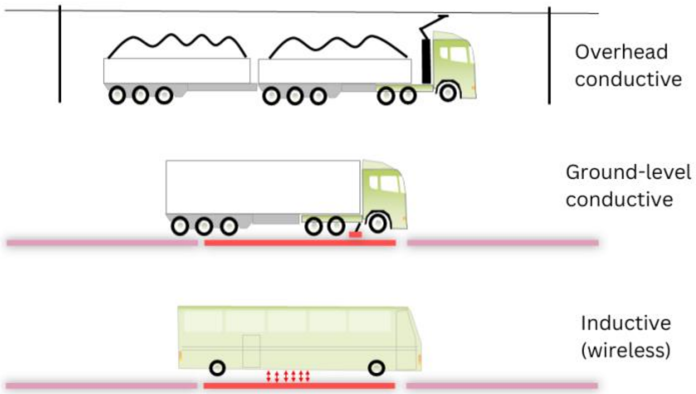

Figure 2.1: ERS types (Börjesson & Gustavsson, 2018)

Each of these systems has unique characteristics that make them suitable for specific applications, and ongoing technological developments continue to shape their deployment and integration strategies within broader transportation networks (Taljegard et al., 2020).

Benefits of ERS

Combining BEHDV with ERS reduces the severity of some BEHDV downsides and offers some additional benefits. Taljegard et al. (2020) underscore the potential of ERS as a high-impact mitigation strategy for the decarbonization of road transport, according to their study in Sweden and Norway. Their analysis suggests that targeting just a quarter of the most trafficked European and national roads with ERS infrastructure could enable electrification of roughly 70% of vehicle-kilometers travelled on those segments, leading to emission reductions of up to 35% across the national road sector. Full-scale implementation, meanwhile, could cut heavy-duty vehicle emissions by as much as 60%. These findings position ERS as an enabler of emission reductions in long-haul freight, particularly when paired with the already lower well-to-wheel emissions of ERS-powered BEHDVs, which are estimated to be 10.5% lower than conventional BEHDVs (Deshpande et al., 2023).

Furthermore, when deployed on high-traffic corridors, ERS demonstrates economic competitiveness, with estimated costs ranging from €0.23 to €0.55 per vehicle-kilometer (Taljegard et al., 2020). While this may include additional charges for infrastructure access beyond electricity costs alone, the overall pricing remains within a viable range for long-haul freight applications

Additionally, ERS offers a reduced vehicle cost. One of high-cost component in BEVs is the battery. Utilizing ERS allows significant reductions in battery size, directly decreasing vehicle cost. According to recent studies, battery packs constitute up to 63% of BEHDV costs, and reducing battery capacity through ERS adoption could significantly decrease overall vehicle prices, potentially accelerating BEV adoption (Shoman et al., 2022). Reduction in battery size not only reduces vehicle cost but also decreases the vehicle's weight, directly lowering the energy required for movement. A smaller battery thus contributes to higher vehicle efficiency and energy savings (Shoman et al., 2022). Deshpande et. al. (2023) estimated that BEHDVs with ERS are 10% more efficient than without it.

Lastly, dynamic charging via ERS allows continuous power delivery, reducing downtime associated with stationary charging infrastructure and enabling greater operational flexibility and efficiency (Shoman et al., 2022; Deshpande et al., 2023). Together, these benefits make ERS-equipped electric trucks a more practical option for sustainable freight economically and operationally.

2.4 Challenges in ERS Implementation

ERS Technological Readiness

While all three main ERS types, overhead conductive, ground-level conductive, and inductive wireless systems, have demonstrated feasibility, they differ significantly in terms of technological maturity and readiness for large-scale deployment. Current evidence suggests that overhead catenary systems are the most mature, benefiting from decades of application in various transport systems. These systems have reached TRL of 8 or higher in critical subsystems such as electricity supply, power transfer, and vehicle integration (Widegren et al., 2022).

Ground-level conductive systems, such as those developed by Elways and Elonroad, have achieved TRL levels between 6 and 7 for most subsystems, though aspects like billing and road operation still lag behind (Widegren et al., 2022). Inductive (wireless) systems, as developed by Electreon, are generally less mature, with several subsystems such as road infrastructure and energy transfer still at TRL 4-6 depending on speed and use case. Lower energy transfer efficiency and installation challenges - such as shallow coil embedding and thermal management - remain barriers to widespread adoption (Mazhoud et al., 2022; Widegren et al., 2022).

Across all ERS technologies, operational subsystems - including energy metering, vehicle identification, and billing - show the lowest readiness levels and present critical challenges for real-world implementation. Consequently, while the core power transfer technologies are advancing, full-system readiness remains uneven, particularly in operational and administrative functions necessary for commercial viability (Widegren et al., 2021), though overhead conductive ERS holds the highest Technology Readiness Level (TRL), with pilot deployments already active in Sweden and Germany (Widegren et al., 2022; Bakker et al., 2024).

High Initial Investment Costs

The implementation of ERS involves significant infrastructure costs, including the construction and maintenance of electrified roads, whether they use overhead lines, rail systems embedded in the road, or wireless technology. The cost-effectiveness of these systems heavily depends on high traffic volumes to offset the initial investment and operational costs. For instance, the estimated cost per kilometer for inductive charging is ranging from 1 to 5 million EUR, significantly higher than other systems like overhead catenary, which is around €2.5 million per kilometer (Börjesson et al., 2021). According to a cost analysis study, the break-even point for ERS can be achieved, but only with substantial freight traffic volumes to justify the expenditures (Schulte & Ny, 2018).

Lack of Standardization

Despite ongoing field trials and pilot projects across Europe, the development of ERS is hindered by a lack of standardization across technological and operational domains. Studies highlight that different ERS technologies are being tested in parallel without a unified framework, leading to fragmented progress and uncertainty for industry stakeholders (PIARC, 2018, Plötz et al., 2024). Standardization efforts are underway but remain incomplete, particularly concerning the interaction between vehicles and infrastructure components like pantographs and current collectors for ground-level systems.

Manufacturers and local stakeholders have expressed concerns over the absence of established operational responsibilities, such as billing and maintenance schemes, as well as the lack of a clear regulatory framework at both national and EU levels. This gap contributes to slow deployment, increased coordination costs, and hesitation from industry actors to commit to long-term investments (Burghard et al., 2024).

Moreover, the lack of interoperability standards threatens the creation of a functional cross-country ERS network. Without harmonized technical specifications and governance models, the risk of stranded assets and fragmented infrastructure increases, undermining the scalability and economic viability of ERS technologies (Linné et al., 2020)

Uncertainty and Risks

Adopting ERS poses several risks and uncertainties that need to be addressed for successful implementation. High initial costs require a path to cost recovery, while the financial model for recovering the costs of ERS infrastructure through user fees or government subsidies remains uncertain. Ensuring a reliable and secure system for measuring and billing electricity usage is critical to avoid losses from fraud or technical failures (Coban et al., 2022).

The success of ERS also depends on public acceptance and willingness to transition to new technologies. Concerns over safety, reliability, and cost can hinder widespread adoption. Addressing these concerns through effective communication and demonstration projects is essential to build public trust (Electreon, 2024). Moreover, ERS implementation involves multiple stakeholders, including government bodies, private companies, and the public. Aligning the interests and actions of these diverse groups is complex and requires robust frameworks for stakeholder analysis and coordination (Wang et al., 2019). For instance, drivers and logistics companies need to adapt to new operational patterns, such as changes in charging behaviours and route planning to use ERS effectively (Wang et al., 2019).

Routing Constraints and Traffic Congestion

The implementation of ERS infrastructure inherently concentrates traffic flows onto electrified roads, typically those with high average daily traffic to ensure economic viability. Consequently, this could limit route flexibility, as vehicles, particularly commercial freight, would likely prioritize ERS-equipped roads to benefit from continuous dynamic charging and lower operational costs. Such routing preferences may exacerbate traffic congestion on electrified segments, leading to increased wear and tear on these roads and potentially reducing overall network resilience by discouraging alternative routing options (Taljegard et al., 2020). This issue underscores the importance of carefully planning ERS networks, considering not only economic and environmental factors but also implications for overall traffic management and route optimization.

2.5 Real-world Implementation of ERS and Related Findings

While much of the academic literature on ERS is centered on simulations or modelling, several countries have progressed to real-world demonstrations. These pilot projects offer valuable insights into the technical feasibility, regulatory challenges, and stakeholder dynamics that will shape future ERS deployments.

Germany has taken a leading role in ERS deployment, focusing on overhead catenary systems for BEHDVs. Three government-funded pilot projects are currently underway:

- ELISA (eHighway Hessen): A 5-km stretch on the A5 near Frankfurt has been in operation from 2019 until 2024, used by commercial fleets for regular freight operations (Die Autobahn, n.d..; Hartwig et al., 2020).
- FESH (Schleswig-Holstein) and eWayBW (Baden-Württemberg): These regional trials complement the national effort by testing ERS in different regulatory and logistical contexts. The eWayBW project features a 4.1km test section on the B462, where hybrid trucks operate daily in real logistics chains (eWayBW, n.d.; Hartwig et al., 2020; Rogstadius, 2023).

Sweden has also been at the forefront of ERS testing. Early projects include:

- eRoadArlanda, which features a 2-km conductive rail embedded in the road near Arlanda Airport (Interreg Europe, 2019., Hartwig et al., 2020).
- SmartRoad Gotland, a 1.6-km inductive charging test route designed for both buses and trucks, operational since 2020 and run by ElectReon (SmartRoad Gotland, n.d.; Bakker et al., 2024).
- A permanent 20-km ERS corridor between Hallsberg and Örebro is in the planning phase, though initial procurement was delayed due to high construction costs (Trafikverket, 2023.; Bakker et al., 2024).

This is not an exhaustive list, but rather a selection of notable projects that illustrate the diversity of ERS technologies and deployment contexts explored to date. A broader survey by PIARC identified 24 pilot projects across 13 countries, categorizing them into lab-scale prototypes, closed test tracks, and active road trials. The review emphasized the importance of these real-world tests in building stakeholder confidence and enabling the regulatory adjustments needed for scaling ERS (PIARC, 2018).

2.6 Conclusion

The literature review highlights BEHDVs as the central technological pathway for decarbonizing road freight transport. Advances in battery cost, energy density, and operational performance have significantly improved the feasibility of BEHDVs, particularly for medium-duty and short-haul applications. However, their widespread adoption in long-haul freight remains constrained by critical infrastructural challenges, including charging downtime, limited range, high power demand, and misalignment between vehicle deployment and charging infrastructure rollout.

ERS have emerged in the literature as a complementary infrastructure solution designed to address these constraints. By enabling continuous energy transfer to BEHDVs during operation, ERS reduces the dependence on large onboard batteries, shortens charging times, and enhances vehicle efficiency. Pilot projects and simulation studies suggest that ERS could unlock significant environmental and operational gains, particularly along heavily trafficked freight corridors. Nevertheless, technological, regulatory, and financial uncertainties, such as high upfront investment, lack of standardization, and coordination complexity. These reasons continue to hinder large-scale ERS deployment.

Importantly, while extensive research exists on the technological and economic aspects of BEHDVs and ERS in isolation, there is a notable gap in comparative assessments that reflect the operational realities and strategic priorities of key stakeholders in the freight ecosystem. The literature often fails to capture how different actors evaluate the trade-offs between BEHDVs with and without ERS across technical, economic, environmental, and social dimensions, and if there is a business case for adoption ERS.

This gap underscores the need for a structured, multi-actor assessment approach. The next chapter addresses this by applying the MAMCA methodology to evaluate the perceived value and feasibility of BEHDV deployment with and without ERS integration, based on criteria grounded in both literature and stakeholder perspectives.

3 Methodology

This chapter outlines the methodological approach used to evaluate the adoption of BEHDVs with and without ERS, applying the MAMCA framework. The section first introduces the MAMCA methodology and then describes how each research step aligns with the framework. Finally, the methods used to address the research questions are detailed.

3.1 MAMCA Framework

The MAMCA methodology was selected as the primary analytical framework due to its suitability for evaluating complex, multi-stakeholder transitions. The MAMCA methodology evaluates projects by integrating various objectives such as social impacts, business objectives, and political priorities. Traditional monetary evaluations often fall short in capturing intangible aspects and externalities, prompting the use of multi-criteria methods (Tsamboulas et al., 2007). Multi-criteria decision analysis (MCDA) not only includes multiple evaluation criteria but also accommodates the objectives of different stakeholders as stakeholder involvement is crucial for the successful implementation of transport measures (Macharis et al., 2012). It is also emphasized to incorporate socio-political aspects into MCDA, advocating for stakeholder integration to improve decision-making (Banville et al., 1998).

MAMCA explicitly addresses stakeholder perspectives, unlike traditional MCDA which may not separate stakeholder analyses. After defining alternatives, MAMCA identifies stakeholder groups, each with unique criteria. The process ensures a comprehensive understanding of stakeholder needs before criteria and indicators are developed. In the evaluation phase, the final analysis compares stakeholder perspectives, guiding decision-makers in implementation paths based on robust, multi-faceted insights.

The following steps outline the MAMCA method application:

1. Problem Definition and Alternatives,
2. Stakeholder Identification,
3. Criteria Formulation,
4. Indicator Definition and Scoring,
5. Criteria Weighting,
6. Aggregation and Scenario Evaluation,
7. Multi-Criteria Analysis and Aggregation,
8. Interpretation and Implementation Considerations.

Step 1: Problem Definition and Alternatives

The first step entails a precise definition of the decision problem and the identification of feasible alternatives. In this study, the alternatives correspond to two distinct transition pathways: the deployment of BEHDVs relying exclusively on static charging infrastructure, and the deployment of ERS-compatible BEHDVs utilizing dynamic charging during operation.

Step 2: Stakeholder Identification

MAMCA begins with a systematic identification of all stakeholder groups who, based on this study approach, have the capacity to influence the adoption of BEHDVs. Based on their involvement in freight transport operations, investment, or regulation, six groups were selected: vehicle manufacturers, carriers, shippers, electrical grid operators, road operators, and freight forwarders. This addresses the first sub-question concerning which stakeholders are involved in the transition process. The identification of relevant stakeholder groups was based on a comprehensive review of the literature and contextual analysis of the freight transport ecosystem. These groups were defined prior to the empirical research, considering their operational, financial, or regulatory roles in the adoption of

BEHDVs and ERS. This method was chosen as a theory-informed foundation was necessary to ensure that all key actors were represented before engaging in empirical data collection.

Step 3: Criteria Formulation

Each stakeholder group has its own priorities and concerns when it comes to adopting electric trucks. To reflect that, a separate set of evaluation criteria was defined for each group. These criteria were informed by interviews with stakeholders and supported by existing literature on electric freight transport. This approach ensures the evaluation captures what actually matters to each group, instead of applying a one-size-fits-all framework. The second sub-question, focused on the evaluation criteria stakeholders use to assess the transition options, was explored through semi-structured expert interviews. This qualitative method was selected due to its flexibility and depth, allowing for the extraction of nuanced stakeholder concerns and priorities that may not be captured through predefined surveys. Semi-structured interviews also ensured consistency across stakeholder groups while allowing for the emergence of group-specific issues. These interviews gathered qualitative insights into stakeholder-specific objectives, concerns, and assessment logic, leading to the definition of tailored evaluation criteria for each group.

Step 4: Indicator Definition and Scoring

To compare the alternatives, each criterion needed to be measurable. For that reason, specific indicators, either quantitative or qualitative, were assigned to each one. Indicators were chosen based on data availability and how well they matched stakeholder priorities. Depending on the case, values were gathered through literature review, expert input, or calculations. Each indicator includes the unit of measurement, the desired direction of performance (i.e., whether a higher value is preferred), and the scoring methodology. Where quantitative data analysis could not be performed, a 1-to-5 Likert

scale was employed for scoring across both scenarios, with score of 1 representing very poor performance and score 5 representing excellent performance. Scoring was based on triangulated evidence from:

- Interview insights
- Literature and technical reports
- Expert judgment

A brief justification for each score was documented, and scores reflect comparative scenario performance rather than absolute values.

Step 5: Weighting of Criteria

Once the stakeholder-specific criteria and indicators are established, weights are assigned to reflect the relative importance of each criterion within its respective stakeholder group. In this study, the BWM is applied for this purpose. In BWM, stakeholders identify the most and least important criteria and then compare the others in relation to those two. The result is a weight distribution that reflects the group's internal priorities. The third sub-question was addressed through a structured weighting exercise using the BWM. This method is explained in detail in the Chapter 3.3 Weighting Criteria Using BWM.

Step 6: Measurement of Performance

In this step, each alternative's performance on the defined indicators is quantified and normalised for comparability across units and scales. Raw values were obtained from empirical calculations, literature, and expert assessments. Qualitative indicators were scored on a 1-5 Likert scale, while quantitative indicators retained their units prior to transformation. A Min-Max normalisation assigned the better-performing scenario a score of 1 and the other a score of 0, with an indifference threshold (0.5 points for qualitative, 10% for quantitative) applied to avoid overstating minor differences. These normalised scores provide the basis for stakeholder-weighted aggregation in the next step.

Step 7: Aggregation and Scenario Evaluation

This step involves the construction of a comprehensive evaluation matrix in which each alternative is assessed against the full set of indicators, set by stakeholder group. The performance scores reflect how well each alternative satisfies the stakeholder-specific criteria, using the previously defined indicators. The weights derived through BWM are directly applied in the MAMCA evaluation matrix, ensuring that each stakeholder group's priorities are quantitatively reflected in the comparison of alternatives. This structured matrix serves as the empirical foundation for multi-criteria analysis. The fourth sub-question addressed through the development of comparative performance indicators for each criterion.

Step 8: Overall Analysis and Policy Recommendations

Finally, the aggregated results are interpreted to derive strategic insights for implementation. The method enables identification of alternatives that enjoy broad stakeholder support, as well as those that generate tension between competing objectives. These insights inform recommendations regarding the viability and acceptance of the transition pathway. Rather than prescribing a single "optimal" solution, MAMCA highlights the conditions under which each alternative becomes favourable, providing a nuanced basis for policy and investment decisions.

3.2 Data Collection and Analysis

Building on the methodological approach outlined above, this section outlines the practical steps taken to collect the data used in the evaluation.

The semi-structured interviews were designed to explore how different stakeholder groups evaluate the transition options. Before the interviews, each participant was informed about the stakeholder groups relevant to this research (see Chapter 4 for details) and was told that they could discuss the perspective of one or multiple stakeholders based on their preference. In every interview, two core questions were asked when discussing each stakeholder: "What specific criteria do you think carriers might prioritize when deciding to adopt BEHDVs?" and "How might these criteria differ with the adoption of ERS?". Interviews were conducted remotely, recorded with participant consent, and subsequently transcribed in full. The edited transcription of every interview can be found in Appendix A. After all interviews were completed, thematic coding was applied to the transcripts to identify recurring concerns, goals, and constraints. These were then translated into stakeholder-specific evaluation criteria, forming the qualitative basis for the MAMCA model.

Following the interviews, a structured survey that is presented in the Appendix C was developed to capture the relative importance of the evaluation criteria using the BWM. The criteria used in the survey were derived directly from the interview findings, ensuring consistency between the qualitative and quantitative phases. For each stakeholder group, participants were asked to identify the most and least important criteria from their perspective and then rate all other criteria in relation to these two anchor points. A simplified 1-to-5 scale was used (instead of the original 1-to-9 BWM scale) to reduce cognitive effort and increase response rate and quality. The resulting comparisons formed the input for the BWM optimization model, which was used to calculate normalized weights for each stakeholder group.

These two phases of data collection - interviews and BWM-based surveys - ensured that stakeholder input was both qualitatively grounded and quantitatively robust, providing a comprehensive foundation for the subsequent MAMCA evaluation.

3.3 Weighting Criteria Using BWM

To understand how each stakeholder group prioritizes the identified criteria, the BWM is used. BWM is a structured multi-criteria decision-making method developed by Rezaei (2015). Compared to traditional methods like AHP, BWM requires fewer pairwise comparisons while often yielding more consistent results. The method is based on identifying two reference points: the best (most important) and the worst (least important) criteria from the decision-maker's perspective. These are then compared to all other criteria as visualised in Figure 3.1, forming two comparison vectors: one for "best-to-others" (A_B) and one for "others-to-worst" (A_W) (Rezaei, 2015; 2016):

- $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$
- $A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})$

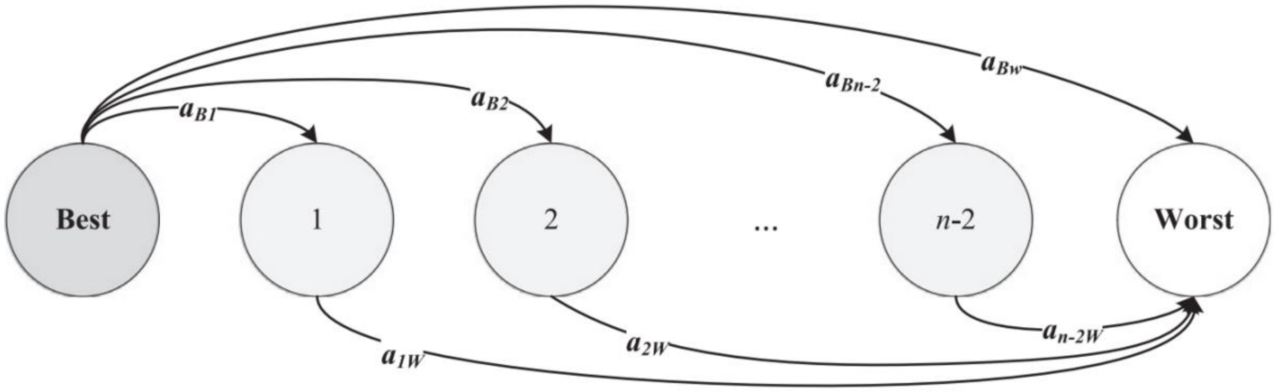

Figure 3.1: Reference comparison visualisation (Rezaei, 2015)

The optimal weights $w_1, w_2, \ldots, w_n$ are determined by solving a linear optimization problem that minimizes the maximum absolute deviation between the pairwise comparisons and the derived weights:

$$\min_{\mathbf{w},\xi} \xi$$
$$\text{subject to:}$$
$$\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi, \quad \forall j$$
$$\left|\frac{w_j}{w_W} - a_{jW}\right| \leq \xi, \quad \forall j$$
$$\sum_{j=1}^{n} w_j = 1, \quad w_j \geq 0, \quad \forall j$$

Where:

- w_B and w_W are the weights of the best and worst criteria.
- a_{Bj} and a_{jW} are comparison values from the A_B and A_W vectors.
- ξ represents the maximum deviation from consistency.

This linear programming model is solved to determine the unique set of weights *w* that best represents the preferences with minimal inconsistency.

Furthermore, a notable feature of BWM is the ability to measure the Consistency Ratio (CR) of the provided pairwise comparisons. To get the CR, ξ is divided by consistency index (CI) which is the maximum allowed deviation for a given comparison intensity which is derived from Rezaei's (2015) benchmark table:

$$CR = \frac{\xi}{CI}$$

A CR close to 0 indicates highly consistent judgments, while values approaching 1 reflect less reliable inputs. When using standard 1-to-9 scale, threshold of CR ≤ 0.3 is usually set to ensure the robustness of the derived weights. Since in this survey 1 to 5 scale was used, the following adjustments were made:

- Since CI values are not present, ξ will be treated as consistency ratio.
- The consistency threshold was reduced by 50% to ≤ 0.15 to address the increased sensitivity, with results having ξ ≤ 0.05 considered as very consistent, 0.05 < ξ ≤ 0.10 - moderate consistency, 0.10 < ξ ≤ 0.15 - acceptable consistency, and ξ > 0.15 inconsistent.

4 Results

This chapter addresses the first, second and third research questions. As outlined earlier, one of the main objectives of this study is to identify the evaluation criteria that different stakeholder groups use when assessing the adoption of BEHDVs and ERS, and to determine the relative importance and performance of these criteria.

4.1 Stakeholders

Successful ERS adoption hinges on the coordinated efforts of multiple stakeholders, each with distinct roles and objectives. All the involved parties and actors must navigate a complex landscape of technological, economic, and regulatory factors. Understanding the perspectives, incentives, and influence of each stakeholder group is crucial for developing effective strategies for ERS implementation. Wang (2023) has mapped the stakeholders and their influence in an ERS adoption (Figure 4.1).

Drawing on existing stakeholder mappings as well as broader academic and policy literature, this section identifies those actors with either high influence or high interest in ERS deployment, those whose engagement is critical to shaping outcomes. It is important to note, that there are many other stakeholders that are involved in the adoption of BEHDV and ERS, or some of the mentioned decision makers can be refined further into multiple subcomponents. This will be addressed in the Limitations section of the thesis.

The sections that follow provide a detailed literature-based review of each group's role, influence, and motivations within the ERS adoption landscape

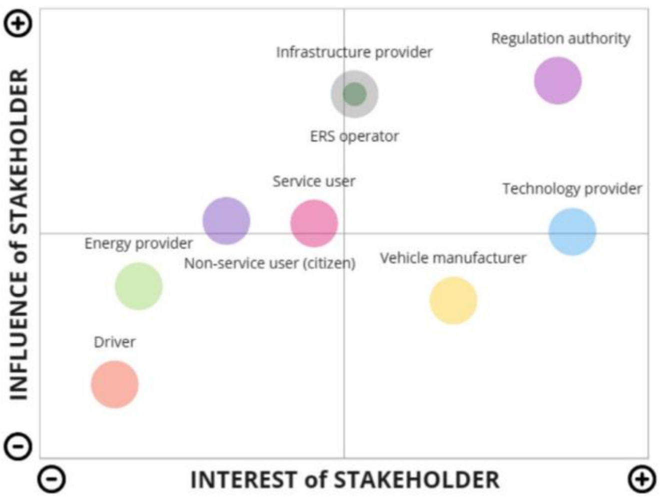

Figure 4.1: Stakeholder mapping based on their interested and influence (Wang, 2023)

Governments

In some cases, the involvement of governments is very limited and includes just the legal aspects; usually when there is a significant economic incentive for all other decision makers to work towards the same goal. In the case of BEHDV, the low adoption numbers display the need of government involvement in some way.

As discussed before, one of the main goals of the modern governments in the European Union is to promote ways to reduce emissions of GHGs. Therefore, governments are motivated working with various stakeholder that are included in the electrification of heavy-duty vehicles. Furthermore, the adoption of vehicles powered by electricity can reduce oil dependency, enhancing national energy security and reducing vulnerability to oil supply and price fluctuations

(Kester, 2018), especially in the light of major global and regional events as COVID pandemic and an active war in Europe.

Having strong motivation for the adoption of decarbonisation technologies, governments may employ various tactics for it. Governments can fund research and development initiatives to advance technology, improve efficiency, and reduce costs (Shoman et al., 2022). Developing technology, though, is not nearly enough to make it widespread. Governments can also establish policies, regulations, and standards to govern the implementation and operation of BEHDVs and ERS. This includes setting safety standards, interoperability protocols, and guidelines for public-private partnerships (PIARC, 2018).

Lastly, governments can offer incentives and subsidies to encourage the adoption of BEHDVs and ERS technologies. This can help offset the initial costs and promote wider acceptance (Aryanpur & Rogan, 2024).

Vehicle Manufacturers

As vehicle manufacturers produce the BEHDVs, they are one of the key decision makers in this stakeholder network. Vehicle manufacturers are privately owned companies that are mostly focused on profits. In a technological transition from, in this case, diesel engines to electrical ones, these companies must ensure that the market share and revenue is maintained. In other words, using BSG product portfolio matrix (Henderson, 1970), vehicle manufacturers must ensure that the cash flow loss from the eventual phase out of the diesel-powered vehicles (currently - cash cows) will be replaced by the BEHDVs that are around the question mark place in the matrix.

Previously discussed governments also often collaborate with manufacturers and technology providers in pilot projects to test and refine ERS technologies. For instance, in Sweden, collaborations between the government and various manufacturers have led to successful pilot projects that test different ERS technologies such as overhead lines and conductive rails in roadways (Erixon, 2017).

To enable on-the-move charging, manufacturers must develop BEHDVs specifically designed for ERS compatibility. This could involve integrating specialized charging equipment or components into their BEHDV models. Adapting their vehicles for ERS would allow manufacturers to market smaller and more affordable battery packs while still providing sufficient driving range, as ERS could reduce required battery capacity by up to 70% (Shoman et al., 2022). Smaller battery would also reduce the reliance on rare earth metals and battery manufactures, whose extraction and manufacturing are currently concentrated in a handful of countries (Spiller et al., 2024). On the other hand, in it important to mention that the reduced vehicle price might also reduce the potential revenue of the vehicle manufacturers, which might not be a desired outcome for them.

Carriers

The creation of new BEHDV does not equal its adoption. Carriers, who generate the demand for BEHDVs will be the initial adopters of both - BEHDVs and ERS (PIARC, 2018). This transition presents a significant challenge, as they must shift their fleets from diesel to electric vehicles and adjust their operations to fit the new infrastructure.

A key factor in achieving widespread adoption within the carrier network is providing sufficient incentives for truck owners to invest in upgrading their fleets. Studies highlight the need to "remove obstacles for transport companies" and create incentives that encourage ERS utilization. This will ensure timely realization of the economic and environmental benefits associated with this new infrastructure, through a rapid market ramp-up (Hartwig, 2021).

At the same time, carriers are particularly sensitive to cost-efficiency, and the use of ERS can be a significant enabler in reducing their operational costs - especially on strategically chosen corridors. Simulation studies comparing diesel and ERS-enabled operations show that, for specific high-traffic routes, ERS-equipped trucks achieve the lowest cost per kilometer for carriers, outperforming other low-carbon alternatives like LNG (Aronietis & Vanelslander, 2024).

These savings stem from both reduced energy costs and the ability to downsize onboard batteries, which further reduces vehicle weight and cost.

Shippers

Shippers are on the other side of the supply-demand graph. The main goal of shippers is to transport the goods from one point to another, and they are mostly indifferent to how it happens while price efficiency is largely the main influencing factor. However, the global sustainability goals are forcing them to look for greener alternative solutions. Therefore, their demand for sustainable logistics solutions can significantly influence the carriers' decision to transition to cleaner technologies.

Despite the environmental pressure, another McKinsey & Company analysis by Bertelè et al. (2024) suggests that more than 80 percent of logistics customers are not willing to pay even as much as a 10 percent premium for a green product. They further estimate that only about 10 percent of customers would be willing to pay a 20 percent premium.

Electrical Grid Operators

The role of electrical grid operators is critical to the implementation and scalability of ERS as they are responsible for ensuring stable electricity transmission and distribution, which must be adapted to accommodate the high concentrated demand for static chargers, and continuous and distributed demand patterns introduced by dynamic charging.

Unlike conventional depot or fast charging infrastructure, which tends to concentrate electricity demand at specific locations and times (e.g., overnight charging leading to evening peak loads), ERS offers the potential to distribute energy consumption more evenly across the day. Modelling from Sweden suggests that ERS usage shifts a substantial portion of charging demand from peak evening hours to daylight hours, thereby reducing peak load from 3 GWh/h to 2.2 GWh/h and easing pressure on the grid (Shoman et al, 2022).

However, realizing these benefits requires extensive coordination with grid operators, particularly concerning the connection of ERS infrastructure to the medium-voltage grid. Wide-area deployment will likely necessitate significant grid reinforcement and expansion, especially along major highways. Furthermore, ERS infrastructure introduces new complexity into grid operations and billing. Grid operators must manage energy flows at multiple substation connection points and coordinate with ERS providers and electricity suppliers (Hartwig, 2021).

Road Operators

Road operators play a pivotal role in the deployment of ERS, as they are responsible for both the physical road infrastructure and, in the case of ERS integration, the supporting electrical infrastructure. Their responsibilities encompass planning, construction, operation, maintenance, repair, financing, and asset management of the ERS infrastructure (Hartwig, 2021).

This integration poses unique challenges. From a technical perspective, road operators must assess how ERS impacts pavement durability, winter service operations, and resurfacing activities. The installation of in-road ERS components, for example, could complicate routine maintenance and necessitate new protective systems, such as vehicle restraint systems and specific crash tests for embedded infrastructure (PIARC, 2018).

Additionally, the installation of ERS entails legal and regulatory complexity, particularly regarding land-use rights and planning permission. In some countries, road authorities may not own the land on which the road is built but only have easement rights, raising questions about the installation of ERS components such as transformers or catenary masts (PIARC, 2018).

Road operators must also engage in coordination across sectors - working with grid operators to secure power access, with vehicle manufacturers to ensure system compatibility, and with national regulators to help shape a viable policy framework. Early adoption by road operators may also include participation in pilot trials, sharing results with other agencies, and contributing to the development of technical standards and installation protocols.

Freight Forwarders

Lastly, there are freight forwarding companies. Freight forwarders are in the unique intermediate position directly interconnecting all of the stakeholders described above, which grants them significant influence over transportation decisions. This stakeholder is often missed in the theorical analysis of heavy-duty truck electrification, but due to its distinctive position in the market, this paper will include them as stakeholders in the further analysis.

Compared to transport providers (carriers) and transport buyers (shippers), freight forwarders play a different role in shaping technology adoption. Carriers might hesitate due to upfront costs or potential range limitations of ERS vehicles. Shippers, on the other hand, may be concerned about potential delays or reliability issues with a new technology. Freight forwarders, however, are not directly responsible for operating vehicles or, in most cases, managing tight delivery schedules.

Having lower risks, they can use their far-reaching partner network to promote ERS adoption. For instance, they may prioritize carriers utilizing ERS technology in their selection process. This approach would create a demand for ERS-equipped vehicles, encouraging carriers to invest in the technology.

Furthermore, freight forwarding companies may have an upper hand with vehicle manufacturers. For instance, sennder Technologies GmbH has an active partnership with Scania, a Swedish manufacturer of commercial vehicles. The partnership specifically aims to drive sustainable freight transportation adoption by removing the barrier of high up-front investment cost for the carriers to operate a BEHDV (sennder, 2017).

4.2 Stakeholder Criteria

A second objective of this research is to identify and structure the key criteria that influence the adoption of BEHDVs, both with and without ERS, in the European road freight sector. Drawing on the MAMCA framework, this section presents the comprehensive set of criteria collected from the industry experts, serving as the foundation for subsequent weighting and further evaluation.

To ensure the criteria reflect the realities and priorities of decision makers identified in the previous section, a series of eleven semi-structured interviews were conducted with senior professionals representing various stakeholder perspectives across the freight transportation ecosystem. The edited transcripts of the interviews can be found in the Appendix A with interview protocol statement is presented in the Appendix B. A short background of every expert who were interviewed can be found in the Table 5.1 while the transcripts also contain introductions that highlight how their knowledge or expertise is connected to the research topic. This qualitative approach enabled the capture of both common themes and stakeholder-specific nuances, ensuring that the resulting criteria are grounded in practical industry experience. However, the interviews focused on the individual perspectives of the experts rather than the official positions of the companies they represent. Furthermore, during the interviews the experts were free to talk about any of the identified stakeholders they were confident to express their opinion on, thus leading to uneven amount of data gathered about the stakeholder groups. Lastly, the interviews weren't limited to discussing perspectives of one stakeholder that might represent best, for example, carrier company representatives identified only carrier criteria or vehicle manufacturer representatives identified only vehicle manufacturer perspectives. Thus, in most interviews, multiple stakeholder criteria were discussed.

Table 4.1: List of interviewed industry experts with a summary of their background related to the thesis topic.

Appendix	Background
A.1	Stakeholder Expert 1: Director at GRUBER Logistics, Vice Chair at ALICE and 2ZERO, with 5+ years of experience in logistics industry.
A.2	Stakeholder Expert 2: Project Leader at Scania, a Swedish heavy-duty truck manufacturer, with 23+ years of experience.
A.3	Stakeholder Expert 3: Director at sennder, a German digital freight forwarder, with 15+ years of experience in various solutions related to climate change.
A.4	Stakeholder Expert 4: Director at ElectReon, a leading provider of wireless charging solutions for electric vehicles, with 15+ years of experience related to ERS.
A.5	Stakeholder Expert 5: C-level executive at JUNA Technologies, a joint venture between Scania and sennder that aims to accelerate the adoption of electric trucks, with 7+ year of experience in electric vehicles.
A.6	Stakeholder Expert 6: C-level executive at POC Energy, a Swedish company that specializes in developing smart charging solutions for various types of vehicles, with 15+ year experience related to vehicle electrification.
A.7	Stakeholder Expert 7: Director at DHL Express, global courier and express logistics company, with 14+ years of experience.
A.8	Stakeholder Expert 8: Business Development Manager at Siemens Mobility Electrification, a division dedicated to electrification solutions for rail and road transport, with 13+ years of experience related to ERS.
A.9	Stakeholder Expert 9: Project Manager at Elonroad, a Swedish cleantech company that focused on ERS development, with 8+ year of experience focusing dynamic charging solutions.
A.10	Stakeholder Expert 10: Project Manager at DAF Trucks, a leading Dutch truck manufacturer, with 23+ years of experience and recent focus advanced technologies related to CO_2 reduction.
A.11	Stakeholder Expert 11: Project Manager at e-netz Südhessen AG, a German regional electricity and gas distribution system operator, with 6+ years of experience working on ERS related projects.

Electrical grid operators were discussed in every interview, shipper, carrier, and vehicle manufacturers were discussed in ten interviews, road operators in seven interviews, while freight forwarders - only in three interviews. Government, as a stakeholder, was not discussed but its impact will be mentioned in the discussion section.

The analysis followed an inductive thematic approach, where responses were systematically coded and grouped into recurring themes. The frequency with which each criterion was mentioned was recorded to provide a preliminary indication of their perceived importance and relevance within the industry. The Tables 4.2, 4.3, 4.4, 4.5, 4.6 and 4.7 provide a structured overview of the identified criteria, accompanied by frequency data. These criteria form the basis for the subsequent weighting exercise and comparative analysis within the MAMCA methodology.

Table 4.2: Carrier criteria that influence the adoption of BEHDVs, both with and without ERS.

Criteria	Definition	Frequency	Interviews
Total Cost of Ownership (TCO)	All lifetime vehicle costs including purchase, operation, and maintenance	9	A.1, A.2, A.3, A.5, A.6, A.7, A.8, A.9, A10
Operational Reliability	Avoiding downtime due to charging time or infrastructure failure	6	A.1, A.2, A.6, A.7, A.9, A.10
Vehicle Payload and Weight	Effect of the vehicle system on transportable cargo weight	5	A.2, A.6, A.7, A.9, A.10
Access to Infrastructure	Availability of charging or energy supply infrastructure across relevant transport corridors	5	A.1, A.2, A.6, A.9, A.10

Driver Satisfaction	Driver comfort, experience, and ease of charging	4	A.2, A.4, A.8, A.10
Flexibility and Asset Utilization	Ease of using trucks across contracts and routes.	2	A.1, A.5

Table 4.3: Shipper criteria that influence the adoption of BEHDVs, both with and without ERS.

Criteria	Definition	Frequency	Interviews
Cost efficiency (freight rates)	Ability to maintain competitive pricing while adopting low-emission transport	10	A.1, A.2, A.3, A.4, A.5, A.6, A.7, A.8, A.9, A10
Sustainability / CO_2 emissions reduction	Contribution of transport operations to emission reduction goals	10	A.1, A.2, A.3, A.4, A.5, A.6, A.7, A.8, A.9, A10
Reliability of delivery schedules	Ability to ensure timely deliveries when using new vehicle technologies	2	A.1, A.6
Well-being of drivers	Ensuring safe and fair working conditions for drivers within the supply chain	1	A.8

Table 4.4: Vehicle manufacturer criteria that influence the adoption of BEHDVs, both with and without ERS.

Criteria	Definition	Frequency	Interviews
Profitability and Customer Demand	Ensuring product-market fit and sustainable business returns	8	A.2, A.3, A.4, A.5, A.6, A.8, A.9, A.10
Standardization and Interoperability	Compatibility of vehicles with widely adopted technical standards	7	A.1, A.2, A.5, A.6, A.8, A.9, A.10
Infrastructure Readiness	Alignment between vehicle capabilities and external charging network development	7	A.2, A.4, A.6, A.7, A.8, A.9, A.10
Long-Term Technology Risk	Uncertainty about which energy technologies will dominate the future market	5	A.1, A.2, A.4, A.8, A.9

Table 4.5: Electrical grid operator criteria that influence the adoption of BEHDVs, both with and without ERS.

Criteria	Definition	Frequency	Interviews
Distributed Load Management	Ability to spread electricity demand to avoid grid bottlenecks	9	A.,1 A.2, A.4, A.6, A.7, A.8, A.9, A.10, A.11
Grid Capacity Constraints	Limitations in local or regional grids to support high charging demand	8	A.1, A.3, A.4, A.5, A.6, A.9, A.10, A.11
Demand Density	Number of users required to justify infrastructure investment	5	A.2, A.6, A.8, A.9, A.11
Policy Stability and Regulatory Support	Long-term regulatory certainty to enable strategic investment	5	A.2, A.8, A.9, A.10, A.11

Table 4.6: Road operator criteria that influence the adoption of BEHDVs, both with and without ERS.

Criteria	Definition	Frequency	Interviews
Investment and Maintenance Needs	Cost and effort required to build and maintain new road-integrated systems	3	A.5, A.8, A.9
Land Use Efficiency	Minimizing the space required for vehicle charging or energy systems	3	A.2, A.4, A.9
Public Acceptance and Visual Impact	Influence of new infrastructure on public perception and landscape aesthetics	3	A.1, A.7, A.8

Table 4.7: Freight forwarder criteria that influence the adoption of BEHDVs, both with and without ERS.

Criteria	Definition	Frequency	Interviews
Cost Stability and Control (Energy Costs)	Managing energy costs with lower price volatility than diesel	3	A.3, A.5, A.8
Operational Efficiency	Ability to efficiently allocate vehicles and plan routes	3	A.3, A.5, A.8
Competitive Advantage	The ability to gain preferential market access and business opportunities by operating compliant zero-emission fleets	2	A.3, A.5
Regulatory Compliance and Sustainability Goals	Meeting emission targets and environmental obligations	2	A.4, A.8

4.3 Thematic Grouping of Criteria

To enable a structured analysis of the diverse criteria identified through expert interviews, the collected stakeholder-specific criteria were consolidated into broader thematic categories. This approach helps clarify interdependencies, highlight recurring priorities, and facilitate cross-stakeholder comparison. The method of thematic grouping is widely used in multi-criteria and stakeholder analysis (Macharis et al., 2012), particularly when evaluating the systemic impact of technological transitions in the transport sector.

For this study, the criteria were consolidated into three main themes, each representing a core dimension of the decision-making process:

1. **Economic and Business Viability:** This theme captures the financial sustainability and market logic underpinning stakeholders' decisions to adopt BEHDVs and ERS technologies. It includes both direct cost considerations - such as TCO, operational efficiency, and infrastructure investment - as well as broader business dynamics like pricing predictability, return on investment, and the potential for strategic differentiation. Stakeholders assess these criteria to determine whether the transition to zero-emission transport solutions aligns with their long-term economic goals, risk tolerance, and competitive positioning in the market.
2. **Operational and Technical Performance**: This theme captures the ability of BEHDVs and ERS to function effectively within existing logistics systems. It encompasses aspects such as operational reliability, payload limitations, route flexibility, infrastructure accessibility, grid capacity, and technology interoperability.
3. **Societal and Environmental Considerations**: This theme brings together the broader impacts of BEHDV and ERS adoption on society, people, and the environment. It includes criteria related to driver satisfaction, public acceptance, land use, CO_2 emissions reduction, regulatory compliance, policy stability, and long-term technology risk. These considerations reflect growing pressures on logistics and transport stakeholders to align their operations with sustainability goals and social responsibility expectations.

Table 4.8 provides a matrix that visualizes how the identified criteria align with the thematic categories across different stakeholder groups. As can be seen from the results, most of the stakeholders have a criterion in every theme.

Table 4.8: Mapping of stakeholder criteria to thematic categories.

Stakeholder	Economic and Business Viability	Operational and Technical Performance	Societal and Environmental Considerations
Shippers	• Cost Efficiency (Freight Rates)	• Reliability of Delivery Schedules	• Sustainability / CO_2 Emissions Reduction • Well-being of Drivers

Carriers	• Total Cost of Ownership (TCO)	• Operational Reliability • Vehicle Payload and Weight • Access to Infrastructure • Flexibility and Asset Utilization	• Driver Satisfaction
Vehicle Manufacturers	• Profitability and Customer Demand	• Standardization and Interoperability • Infrastructure Readiness • Long-Term Technology Risk	
Electrical Grid Operators	• Demand Density	• Distributed Load Management • Grid Capacity Constraints	• Policy Stability and Regulatory Support
Road Operators	• Investment and Maintenance Needs	• Land Use Efficiency	• Public Acceptance and Visual Impact
Freight Forwarders	• Cost Stability and Control (Energy Costs) • Competitive Advantage	• Operational Efficiency	• Regulatory Compliance and Sustainability Goals

4.4 Criteria Weights

To answer the third research question, an online survey was sent to eleven interviewed industry experts, who were interviewed to gather the criteria for every stakeholder, and eight responses were received. Jotform online survey building tool was used to create the survey as it provided high level of survey customisation and TU Delft branding. The survey was customised for every expert based on the stakeholders that were discussed during the interviews to avoid overloading them with not relevant questions and to ensure high completion rate. The survey itself was structured according to the BWM, all the questions can be found in the Appendix C. Shippers, carriers, vehicles manufacturers, and electrical grid operators had seven complete answers, road operators - four, and freight forwarders - only two. These numbers are different for every stakeholder group due to the way how interviews were conducted, allowing the experts to discuss only the stakeholder groups that they feel comfortable discussing based on their knowledge.

Consistency ratios, further represented by ξ, for every answer can be found in the Appendix D. Since 1-to-5 scale was used instead of typical 1-to-9, inconsistency becomes more sensitive to even small errors. Therefore, standard ξ value meaning needed to be adjusted accordingly to interpret the consistency of the results correctly. As there no strict threshold defined in the literature for such a scale and as mentioned in the methodology section, ξ range values were divided by two to address the increased sensitivity. When analysis results per stakeholder group, all stakeholders apart from carriers had an acceptable consistency average ξ (between 0.08 and 0.1) while carrier ξ was on the verge of being very consistent with $\xi = 0.067$. Furthermore, out of 34 answers, 4 were very consistent ($\xi \leq 0.05$), 19 were moderately consistent ($0.05 < \xi \leq 0.10$) and 11 were acceptable consistency ($0.10 < \xi \leq 0.15$). If the standard interpretation of this ratio would be used, all answers would be either very high or moderately consistent.

To calculate weights, two BMW solvers were used to ensure the consistency of calculations. As BWM framework is individual by design and estimates the weight for every response, the weight of every criterion was calculated using arithmetic mean of every response. Additionally, standard deviation and coefficient of variation were calculated:

- Standard deviation (SD) quantifies how much individual responses differ from the average weight - higher values indicate more disagreement among respondents.
- Coefficient of variation (VR) shows how large the disagreement is compared to the criteria's importance. It is calculated by dividing SD by the average weight. A high VR suggests inconsistent prioritization between the responders.

The weight data for every criterion and stakeholder group is summarized in the Appendix E.

Carriers

The carrier criteria weights are visualised in the Figure 4.2. For carriers, TCO is by far the top priority, reflected in both its leading average weight (0.283) and high internal agreement (SD = 0.052, CV = 18%). This criteria's dominance aligns with the operational logic of carriers, who prioritize long-term cost predictability and vehicle investment recovery. Other criteria such as operational reliability, vehicle payload and weight, and flexibility and asset utilization were ranked with moderate weights (ranging from 0.144 to 0.169) and exhibited somewhat higher but still acceptable levels of variation (CVs between 20% and 37%). Driver satisfaction and access to infrastructure received lower weights (0.064 and 0.187 respectively), though the latter showed the highest variability in this group (SD = 0.083, CV = 44%), suggesting infrastructure access is viewed quite differently depending on operational context or national charging network maturity. Overall, carriers show one of the strongest internal alignments among all stakeholder groups, with the lowest average SD (0.05) and a relatively low mean CV of 31%. The table the summarised survey result variability based on the stakeholder can be found in the Appendix F.

Shippers

The shipper criteria weights are visualised in the Figure 4.3. In the case of shippers, cost efficiency stands out as the dominant priority, with an average weight of 0.461. Despite moderate absolute variation (SD = 0.1), the relative disagreement among respondents is low (CV = 22%), indicating a well-aligned view on the importance of transportation cost reduction. The next two criteria, sustainability / CO_2 emissions reduction and reliability of delivery schedules, received nearly identical average weights (0.209 and 0.216 respectively), yet were characterized by substantially higher levels of relative variability (CVs of 51% and 59%). This suggests differing levels of emphasis among shippers, likely influenced by varying levels of sustainability integration into procurement practices or differing tolerance for delivery delays. Well-being of drivers, while clearly the least prioritized (weight = 0.115) similarly to driver satisfaction from the carrier side, still attracted a wide range of opinions (CV = 52%), indicating some respondents view it as more strategically relevant despite its overall low ranking. In comparison to other stakeholder groups, shippers fall into the middle tier with respect to internal consistency, with an average SD of 0.099 and a mean CV of 46%.

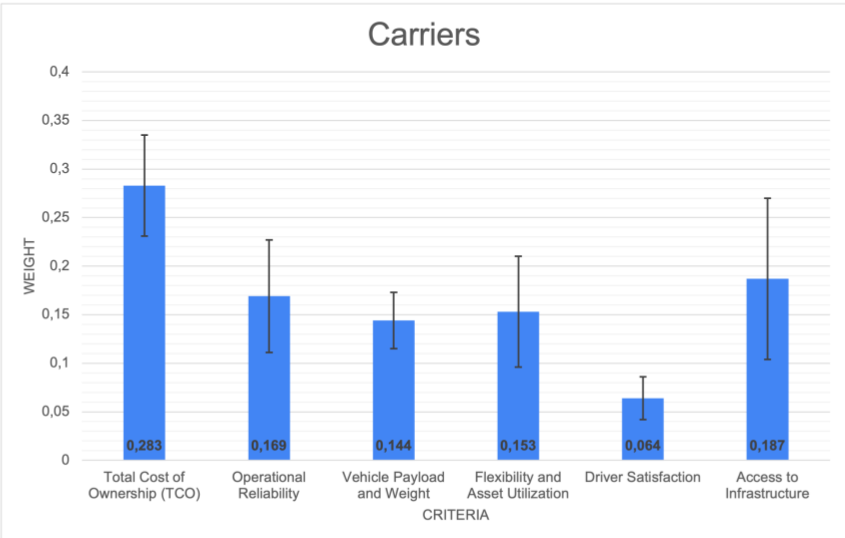

Figure 4.2: Carrier criteria weights with standard deviations.

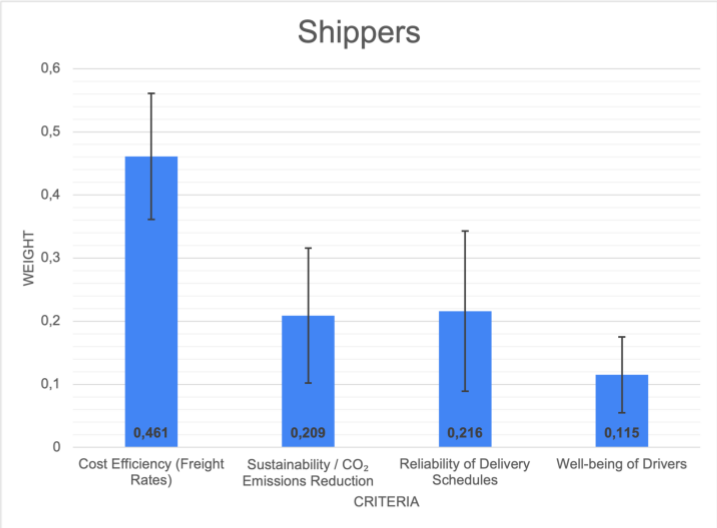

Figure 4.3: Shipper criteria weights with standard deviations.

Vehicle Manufacturers

The vehicle manufacturer criteria weights are visualised in the Figure 4.4. For vehicle manufacturers, the priority is clearly profitability and customer demand, which received the highest weight (0.495) across all criteria considered and exhibited strong agreement among respondents (SD = 0.07, CV = 14%). The next two criteria - infrastructure readiness, and standardization and interoperability - were weighted at 0.220 and 0.171 respectively, and both showed low levels of variability, suggesting consistent stakeholder perceptions (CVs below 20%). Long-term technology risk, although assigned the lowest average importance (0.114), revealed considerably more variation (SD = 0.052, CV = 46%), indicating different views on the long-term implications of technological and infrastructure lock-in. Among all stakeholder groups, vehicle manufacturers demonstrated the strongest internal consensus, with the lowest average SD (0.048) and CV (23%).

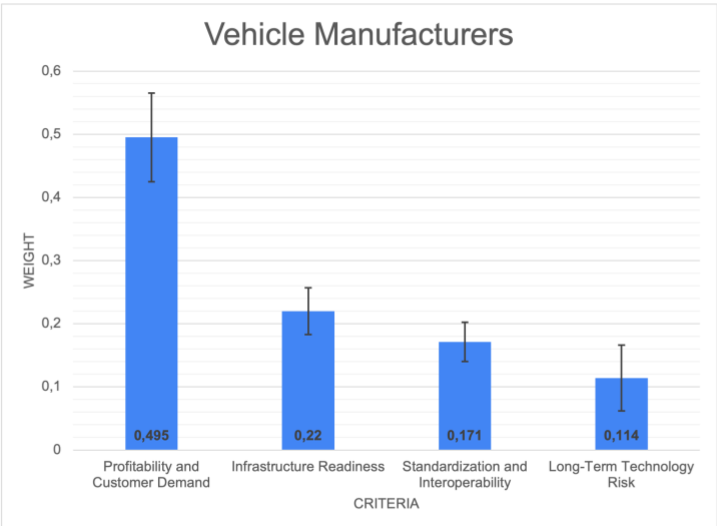

Figure 4.4: Vehicle manufacturer criteria weights with standard deviations.

Electrical Grid Operators

The electrical grid operator criteria weights are visualised in the Figure 4.5. From the viewpoint of this stakeholder, grid capacity constraints is the most critical factor (weight = 0.371), supported by relatively consistent assessments (SD = 0.093, CV = 25%). Policy stability and regulatory support followed closely with a weight of 0.306, although with slightly more variation (CV = 29%). By contrast, demand density and distributed load management were given lower average weights (0.18 and 0.144), yet both showed substantial variation in ratings (SDs around 0.08-0.11 and CVs exceeding 55%). This pattern suggests that while there is some alignment on the importance of managing capacity and ensuring regulatory clarity, opinions differ when it comes to the scalability and load distribution. Overall, the electrical grid operators' results exhibit moderate internal variability, with an average SD of 0.093 and CV of 42.5%.

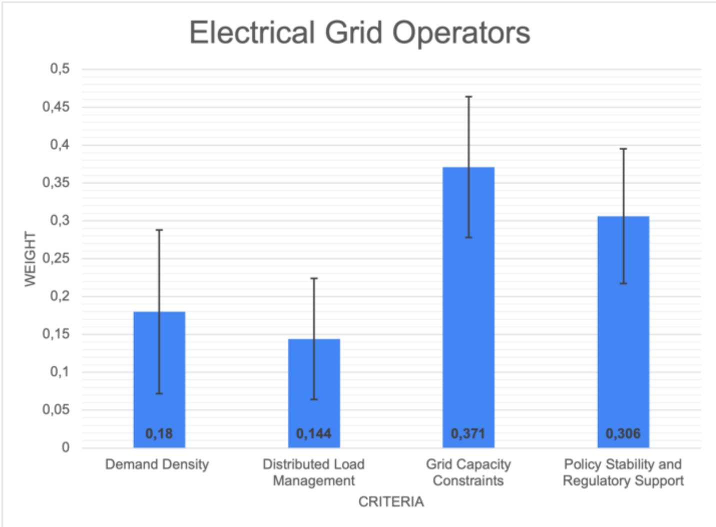

Figure 4.5: Electrical grid operator criteria weights with standard deviations.

Road Operators

The road operator criteria weights are visualised in the Figure 4.6. Among road operators, investment and maintenance needs is the most relevant concern, receiving a weight of 0.471 and a moderately dispersed range of responses (SD = 0.133, CV = 28%). Land use efficiency also figures with the weight of 0.38, though with higher disagreement among respondents (SD = 0.17, CV = 44%), possibly reflecting differing infrastructure constraints across regions, as the responders were based in Italy, Sweden, and Germany. The least important but still relevant factor is public acceptance and visual impact, which was assigned a weight of 0.145. Despite its lower weight of 0.145, this criterion still showed a relatively high CV of 43%, indicating that perspectives on societal acceptance and visual disruption vary. Compared to other stakeholder groups, road operators are in the upper-middle range of internal variability, with an average SD of 0.122 and CV of 38%.

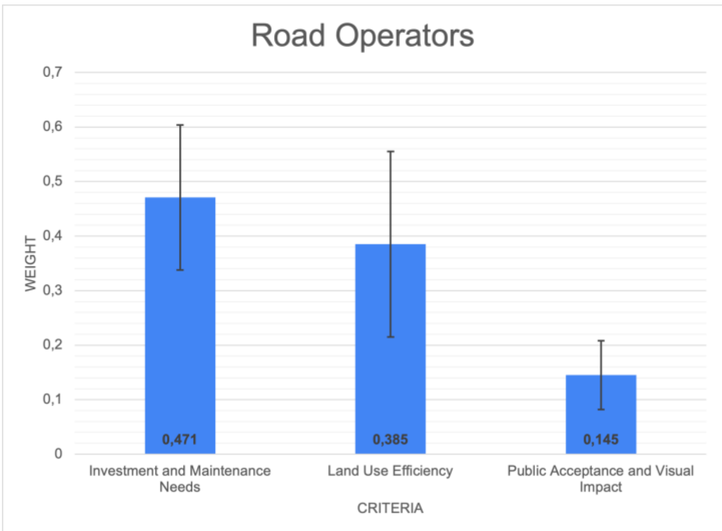

Figure 4.6: Electrical grid operator criteria weights with standard deviations.

Freight Forwarders

Lastly, the freight forwarder criteria weights are visualised in the Figure 4.7. Freight forwarders place the greatest emphasis on operational efficiency, which received the highest weight (0.376) among their criteria and was evaluated with moderate consensus (SD = 0.127, CV = 34%). Regulatory compliance and sustainability Goals and cost stability and control followed with weights of 0.308 and 0.169, but both exhibited high relative disagreement - especially the latter, which had a CV of 75%, the highest among all criteria across stakeholder groups. Lastly, competitive advantage was rated as the least critical (weight = 0.147), though it too showed moderate dispersion in responses (CV = 42%). It is important to note that these high SD and CV values should be interpreted with caution, as they are based on a limited response base of only two participants, which amplifies the effect of any individual difference. In terms of internal coherence, freight forwarders displayed the greatest variability of all groups, with an average SD of 0.127 and CV of 53%.

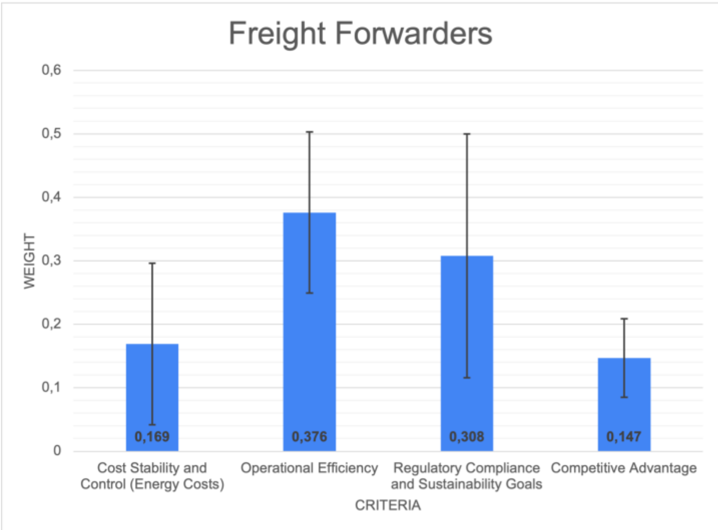

Figure 4.7: Electrical grid operator criteria weights with standard deviations.

4.5 Cross-Criteria Thematic Analysis

To gain another insightful perspective on the distribution of weights across criteria, the individual criteria were grouped according to the thematic categorization introduced in Chapter 4.3. This grouping - comprising Economic and Business Viability, Operational and Technical Performance, and Societal and Environmental Considerations- allows for a higher-level synthesis of stakeholder preferences, highlighting which types of concerns are prioritized most and where difference in opinion is more noticeable. The weights of the criteria belonging to these themes are visualised in Figure 4.8 while more detailed information can be found in Appendix G.

The economic and business viability emerges as the most emphasized category, with a mean weight of 0.315. This theme includes factors such as cost efficiency, total cost of ownership, and profitability - all of which are critical for stakeholders with commercial decision-making responsibilities. The average SD of 0.093 and CV of 37% indicate a moderate level of agreement among respondents. While this suggests that economic viability is widely valued, the spread of opinions also implies some differences in how essential each economic criterion is perceived across stakeholder types.

The second most prioritized theme is operational and technical performance, which includes infrastructure readiness, operational reliability, and vehicle-related performance concerns. It has a significantly lower average weight of 0.221, reflecting its role as a foundational enabler rather than a primary driver of adoption decisions. The average SD for this theme is 0.079, and its CV stands at 36%, pointing to a relatively consistent assessment of the importance of technical and functional aspects across stakeholders. This balance between moderate importance and strong agreement suggests that while these criteria may not dominate strategic discussions, their operational relevance is largely undisputed.

Societal and environmental considerations is the least prioritized theme, with a mean weight of 0.191. Despite including highly visible issues such as CO_2 emissions, driver well-being, and public acceptance, this category trails behind in terms of overall importance. Furthermore, it displays the highest variability, with an average SD of 0.089 and a CV of 45%. This elevated CV suggests substantial difference in how different stakeholders value societal and environmental concerns, likely reflecting their varying exposure to regulatory pressure, public visibility, or internal sustainability mandates. The data implies that while societal factors are acknowledged, their perceived criticality is uneven and more context-dependent than economic or technical aspects.

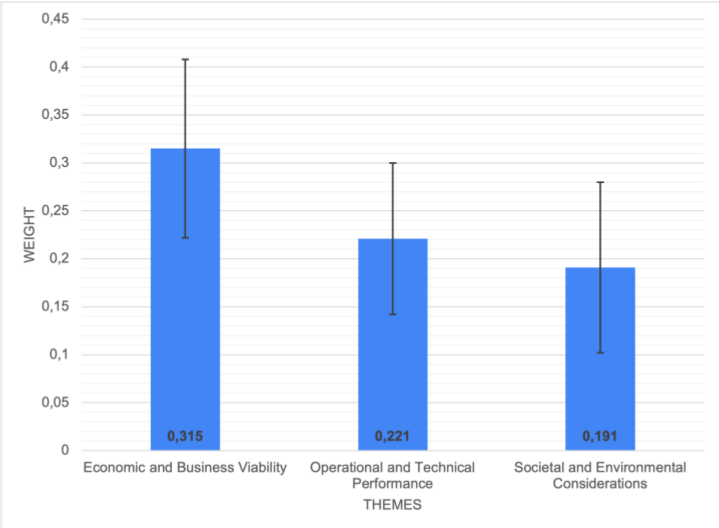

Figure 4.8: Criteria weights and standard deviations based on their theme

Overall, this theme-based analysis reinforces the earlier stakeholder-specific findings: economic and operational drivers tend to unite respondents, whereas societal and environmental criteria bring up more fragmented perspectives. This insight is especially relevant for policymakers or infrastructure planners seeking multi-stakeholder alignment, as it highlights the areas were communication, incentive alignment, or regulatory clarity may be most needed.

4.6 Measurable Indicators

In line with the MAMCA methodology, the next stage of this research focuses on operationalizing the qualitative insights gathered from expert interviews into measurable indicators. To help with a structured comparison of preferences across these groups, quantifiable indicators are defined that can be used to evaluate the relative performance of scenarios. While many criteria in this analysis can be quantified through direct numerical indicators (e.g., cost per kilometre, payload ratio), certain aspects - such as user satisfaction, flexibility, or public acceptance - do not lend themselves easily to precise measurement. In these cases, a Likert-type scoring system is applied to translate qualitative assessments into ordinal values on a consistent scale (1-to-5). The Table 4.9 contains definitions of every score. This allows for the integration of subjective insights into the MAMCA framework while preserving comparability across scenarios and stakeholder perspectives.

Table 4.9: Likert scale definitions for qualitative performance indicators.

Score	Definition
1	**Very Low Performance**. The dimension, criteria, or scenario performs poorly with significant disadvantages, limitations, or risks perceived by stakeholders.
2	**Low Performance.** The dimension, criteria, or scenario presents clear weaknesses or limitations that may hinder its acceptance, usability, or effectiveness under this criterion.
3	**Moderate Performance**. The dimension, criteria, or scenario performs adequately, with a mix of strengths and weaknesses. Acceptable but not particularly strong.
4	**High Performance**. The dimension, criteria, or scenario performs well, with clear advantages and limited drawbacks. It is generally viewed positively.
5	**Very High Performance**. The dimension, criteria, or scenario performs exceptionally well, offering clear and consistent advantages with minimal or no drawbacks perceived by stakeholders.

Furthermore, for BEHDV + ERS scenario quantitative analysis where real world empirical data is required, overhead conductive ERS type will be used in the analysis as it has the most relevant research publications and testing. The other two types will be considered in qualitative analysis sections, as they can affect some of the criteria when comparing to the overhead conductive type.

Carriers

Total Cost of Ownership

TCO refers to the comprehensive financial cost associated with owning and operating a BEHDV across its entire lifecycle. This includes capital expenditure (CapEx), operational expenditure (OpEx), and end-of-life considerations. Given the operational focus of carriers, a per-kilometre cost indicator is chosen to allow for comparability across scenarios.

$$TCO = Acquisition + Infra + Energy + Maintenance - Residual$$

- **Vehicle acquisition cost**: Initial purchase price of a BEHDV. For the ERS scenario, this may include a price premium for ERS compatibility.
- **Access to charging infrastructure**: Cost borne by the carrier for access to energy infrastructure. In the ERS scenario, this includes access fees or per-use charges for dynamic charging infrastructure.
- **Energy cost**: Calculated based on average energy consumption (kWh/km) and electricity prices, accounting for potential efficiency gains through ERS (e.g., reduced battery cycling).
- **Maintenance cost**: Includes scheduled and unscheduled maintenance over the vehicle's lifespan
- **Residual value**: Estimated end-of-life value of the vehicle, subtracted from total cost.

For this criterion, TCO per kilometer will be used as an indicator. A vehicle lifetime distance of 550 000 km is assumed, based on a five-year operational horizon with an annual mileage of 110 000 km, consistent with long-haul applications (Bhardwaj & Mostofi, 2022).

In the battery-only configuration, the acquisition cost of a BEHDV is estimated at 170 000 EUR (Bhardwaj & Mostofi, 2022). Energy consumption is assumed to be 1.44 kWh/km, based on typical values for long-haul BEHDVs (Bhardwaj & Mostofi, 2022). Using an average European commercial electricity price of 0.12 EUR/kWh (Bhardwaj & Mostofi, 2022; Danielis et al., 2025), the total energy cost amounts to 95 040 EUR over the lifetime distance. Maintenance costs are estimated at 6250 EUR per year, totalling 31 250 EUR over five years (Bhardwaj & Mostofi, 2022). Road user charges (tolls) are assumed at 0.09 EUR/km, corresponding to 49 500 EUR for the reference distance (Bhardwaj & Mostofi, 2022). This reflects the reduced access fees already applied to zero-emission trucks compared to diesel vehicles. No residual value is included due to the lack of established resale markets and the high variability in estimates (Danielis et al., 2025).

In the ERS-supported scenario, the acquisition cost can be calculated by adding the additional costs for the integration of pantographs and onboard control units required for dynamic charging compatibility that is estimated to be up to 8000 EUR (Taljegard et al., 2020). Furthermore, it is assumed that compatibility with ERS allows to reduce the battery size up to 50% and battery amounts to 47% of the BEHDV price. Even though according to Rogstadius et al. (2023), the battery size can be reduced up to 65%, that is an optimistic scenario. Meanwhile, the battery share of the cost of the BEHDV is derived from calculation that BEHDV battery capacity is 800 kWh, same as in Bhardwaj & Mostofi (2022) paper, while battery packs are price at 115 USD/kWh, resulting to 92 000 USD (or 80 000 EUR) price for BEHDV battery (European Commission, 2024). This leads to a reduction of vehicle cost by 40 000 EUR. Furthermore, energy consumption is slightly lower due to reduced vehicle weight and direct power transfer. Battery weight savings are roughly 4700 kg which represents around 10% of the fully loaded total vehicle weight (for exact calculations, see indicator Vehicle Payload and Weight section). Therefore, an assumption is made that energy consumption is estimated to be 90% of BEHDV at 1.3 kWh/km. Using the same electricity rate of 0.12 EUR/kWh, the energy cost totals 85 800 EUR over the lifetime. Maintenance costs are assumed to increase slightly by 5% to 6560 EUR per year (or 32 800 EUR total) due to the addition of ERS-specific components, although the literature indicates that ERS could lower battery degradation rates and may reduce long-term service needs (Danielis et al., 2025). For road user charges, we assume that ERS trucks would continue paying the same reduced tolls applicable to zero-emission vehicles, similar to BEHDVs without ERS. The carrier's share of ERS infrastructure access cost is conservatively estimated at 0.094 EUR/km, or 51 700 EUR over the total distance (Börjesson et al, 2021).

Table 4.10: TCO/km comparison for BEHDV and BEHDV + ERS scenarios.

Component	BEHDV	BEHDV + ERS
Vehicle Acquisition	170 000 EUR	138 000 EUR
Energy Cost	95 040 EUR	85 800 EUR
Maintenance	31 250 EUR	32 800 EUR
Tolls	49 500 EUR	49 500 EUR
Infrastructure Charges	-	51 700 EUR
TCO	345 790 EUR	357 800 EUR
TCO/km	0.629 EUR/km	0.651 EUR/km

The final TCO/km figure for BEHDV and for BEHDV + ERS in Table 4.10 and, according to the calculations, the BEHDV + ERS scenario tends to increase the TCO by around 5%. To summarize, even though battery size is reduced by 50%, the additional cost for the integration of pantographs and onboard control units required for dynamic charging compatibility and infrastructure chargers significantly offsets the savings.

Operational Reliability

Operational reliability refers to the degree to which the charging system enables continuous logistics operations with minimal disruption or planning complexity. For BEHDVs without ERS, operations are constrained by the need to stop and recharge, which introduces delays. In contrast, ERS-equipped vehicles can charge while driving, reducing downtime but adding route rigidity due to limited ERS coverage. Additionally, reliability of the functioning charging infrastructure is also essential as the vehicle operators must be sure that they will be able to charge the truck were they planning to do based on their route.

Recent modelling by Cheng & Lin (2024) shows that, even when charging is perfectly aligned with the mandated driving- and rest-periods, every long-haul run still takes 16-32 % longer than the diesel baseline. Put differently, for each hour of productive driving a BEHDV must spend about 19-25 minutes parked and plugged in. This systematic delay, together with the uncertainty of charger availability and uptime along the route, constrains the day-to-day reliability of purely battery-dependent operations.

On the other side, since ERS technology is not yet widely deployed for commercial trucks, empirical data on the charging and routing detours remains limited. The main difference compared to static charging is that ERS trucks might need to driver additional distance and thus take more time to follow electrified road. Estimations of charging-induced operational disruption must rely on theoretical modelling. Bakker et al. (2024) simulate ERS deployment scenarios across the Dutch and European transport networks and introduce a threshold for maximum allowable detour when rerouting to access ERS infrastructure. This threshold is set between 10 and 20% to ensure operational viability without imposing excessive route deviations. For transport flows that meet this constraint, it is assumed that trucks can dynamically recharge over substantial segments of their journey. However, minor off-corridor deviations may still be required to enter or exit the ERS, depending on the spatial alignment of the network with existing freight corridors. Bakker et al. (2024) apply a detour threshold of 10% as a cap for adoptable flows, although most qualifying routes are expected to fall below this value.

Because BEHDVs without ERS must absorb the 16-32 % journey-time penalty for long-haul runs, their operational reliability is inherently lower than that of ERS trucks, whose extra distance is at about 10-20% by current European planning studies, that can be translated for this indicator to 10-20% increase in journey time. It is important to note, that Cheng & Lin (2024) research was done in North America and the data in Europe could differ. The distributed, in-motion nature of ERS charging also mitigates single-point failures that can strand a battery-only fleet at an out-of-service charging location. Although, all the ERS figures above are model based. No heavy-duty ERS corridor is yet in commercial service and until large-scale deployments are built and operated, true reliability data for ERS cannot be measured, so the comparative advantage shown here should be regarded as provisional.

Vehicle Payload and Weight

Vehicle payload and weight refers to how the design and energy storage system of a truck impacts the legally permissible and operationally efficient cargo weight. For carriers, maximizing payload while remaining within legal limits is directly tied to business opportunities and profitability. BEHDVs often suffer from added battery weight, reducing payload capacity. ERS can mitigate this by allowing for smaller onboard batteries, preserving or improving payload. To compare these options, payload-to-total-weight ratio will be used as an indicator.

For this criterion, payload per weight ratio will be used as an indicator. Higher ratio means that the BEHDVs can carry more payload relatively to its weight, thus offering higher efficiency. To contextualize the implications of battery mass in long-haul applications, the ratio of net payload to total vehicle weight under different battery configurations was estimated. BEHDVs equipped with a 1111-kWh battery system has an estimated battery mass of 7293 kg. According to simulation results, this configuration supports a maximum payload of 20900 kg and payload-to-total-weight ratio of approximately 0.52 (Teichert et al, 2023). By comparison, ERS-enabled scenarios allow for significantly smaller onboard battery capacities, reduced by around 65%, because vehicles receive power dynamically while driving (Rogstadius et al., 2023). Using the same energy-to-weight ratio, the ERS battery would weigh around 2552 kg. Including an estimated 300 kg for the ERS collector unit (Bakker et al., 2024), the net payload would be 23365 kg and payload-to-total-weight ratio - 0.58. An improvement of over 10% in payload capacity compared to the battery-only configuration.

Flexibility and Asset Utilization

Flexibility and asset utilization refer to the extent to which heavy-duty vehicles can be deployed across a variety of routes, customer contracts, and operational contexts without incurring significant logistical constraints or economic inefficiencies. For carriers, maintaining high levels of asset utilization and operational adaptability is essential to meet fluctuating customer demands and optimize return on investment. In this study, flexibility is understood not only as a function of technical vehicle capabilities but also as the operational latitude afforded by the supporting infrastructure.

While BEHDVs allow for route planning based on static charging availability, the introduction of ERS presents a different operational paradigm. Vehicles dependent on ERS must follow specific electrified corridors, potentially reducing dispatch flexibility and increasing operational complexity.

Because this criterion varies widely depending on context and is hard to quantify, this study uses a qualitative measure called Operational Flexibility Assessment (the degree to which a vehicle can be reassigned to different routes without requiring significant planning adjustments, additional infrastructure, or incurring operational inefficiencies) that contains five dimensions that are analysed in Table 4.11.

Table 4.11: Operational Flexibility Assessment for BEHDV and BEHDV with ERS.

Dimensions	BEHDV	BEHDV + ERS	References
Route Flexibility	**Moderate Performance**. Vehicles can be dispatched across a wide range of routes. Flexibility is constrained mainly by battery range and charger availability.	**Very Low Performance**. Route choice is limited to ERS corridors. Off-corridor deployment requires larger battery use, undermining the ERS advantage.	Speth & Funke (2021); Shoman et al, (2022); Interview with Stakeholder Expert 10 (A.10)
Asset Reassignment Flexibility	**Moderate Performance**. BEHDV assignments are tied to existing static charging infrastructure, making redeployment logistically somewhat difficult without extensive planning.	**Very Low Performance**. Assignments are fully tied to existing ERS coverage.	Speth & Funke (2021); Cheng & Lin (2024); Shoman et al, (2022); Interview with Stakeholder Expert 4 (A.4)
Charging Infrastructure Dependence	**Low Performance**. Relies on functioning depot or public chargers, but there is fallback through geographic redundancy (i.e., using nearby chargers).	**Very Low Performance**. Entirely dependent on fixed linear infrastructure. A single outage or gap in ERS coverage can disable route viability without major battery fallback.	Speth & Funke (2021); Cheng & Lin (2024); Shoman et al, (2022); Interview with Stakeholder Expert 4 (A.4)
Flexibility for Cross-Border Operations	**Moderate Performance**. Charging compatibility and vehicle weight restrictions vary between countries, requiring advanced planning and posing operational risks. Payment for electricity usage is a problem.	**Low Performance**. Without international ERS standardization and corridor continuity, vehicles lose the ability to operate beyond national coverage zones.	PIARC (2018); Aronietis & Vanelslander (2024); Interview with Stakeholder Expert 1 (A.1) & Stakeholder Expert 7 (A.7)
Resilience to Infrastructure Failures	**Moderate Performance**. Depends on the static charging infrastructure density and operational planning that considers possible failures.	**Moderate Performance**. While it is more robust to local failures, regional or long-distance failures might cause significant issues due to smaller battery pack.	PIARC (2018); Interview with Stakeholder Expert 2 (A.2)

BEHDVs with static charging offer higher operational flexibility than ERS-equipped vehicles, even though it's still relatively low if to compare with diesel trucks, as they can be reassigned across routes with fewer infrastructure constraints and greater resilience to disruptions. In contrast, ERS systems limit flexibility to predefined corridors and are highly vulnerable to infrastructure failures. From a carrier perspective, BEHDV-only technology is therefore the more adaptable option with the average score of 2.8 compared to 1.6 in BEHDV + ERS scenario.

Driver Satisfaction and Ease of Operations

Driver satisfaction and ease of operations refer to how vehicle-related factors such as driving comfort, operational simplicity, and charging convenience influence day-to-day performance, driver recruitment and long-term driver retention. Given the ongoing driver shortage in the freight industry, ensuring a positive and manageable operational experience is a strategic priority for carriers. Technology transitions - such as the shift from diesel to BEHDVs and ERS - can substantially affect the driver experience. This criterion includes elements that are inherently subjective and user-dependent, therefore, a qualitative indicator is derived - Driver Experience Rating. The dimensions of this rating and summarized results are presented in the Table 4.12.

Table 4.12: Driver Experience Assessment for BEHDV and BEHDV with ERS.

Dimensions	BEHDV	BEHDV + ERS	Reference
Driver Comfort	**High Performance**. Drivers report quiet cabins, less vibration, and good torque, leading to improved comfort and reduced fatigue. Although, charging is still manual.	**Very High Performance**. Same noise and vibration benefits as BEHDV-only. Additionally, eliminates the stress of finding charging stations and work manually plugging in the charger.	Interview with Stakeholder Expert 10 (A.10) Stakeholder Expert 2 (A.2), Stakeholder Expert 1 (A.1)
Charging Logistics	**Low Performance**. Charging requires active planning, may lead to delays if chargers are full or underpowered. Adds stress and operational complexity for the driver.	**High Performance**. ERS removes the need for charging stops, simplifying route planning and aligning naturally with legal rest breaks.	Bhardwaj & Mostofi (2022); Interview with Stakeholder Expert 10 (A.10), Stakeholder Expert 8 (A.8)
Ease of Operation	**Moderate Performance**. Drivers must coordinate charging schedules, sometimes suffer from inconsistent charging power, and contend with inadequate infrastructure design for trucks.	**Very High Performance**. Charging while driving simplifies workflow and reduced the need of physically connecting the charger to the vehicle.	PIARC (2018); Interview with Stakeholder Expert 1 (A.1), Stakeholder Expert 8 (A.8)
Safety	**High Performance**. Familiar road surface with no modifications. Charging infrastructure is located at rest areas or depots. Although, Megawatt chargers are excluded from the comparison.	**Low Performance**. ERS road modifications introduced additional infrastructure, like poles and wires, that might cause additional danger in case of an accident.	Speth & Funke (2021); PIARC (2018); Cheng & Lin (2024)
Driver Recruitment & Retention	**Very High Performance.** Clean vehicles and reduced noise improve working conditions, appealing to younger drivers.	**Very High Performance**: Same as for BEHDV-only. Predictable schedules and fewer logistics tasks (no charging planning) may further support retention.	Noto & Mostofi (2023), Interview with Stakeholder Expert 1 (A.1), Stakeholder Expert 2 (A.2)

From the perspective of driver satisfaction and ease of operations, ERS scenario has an advantage with the score of 4.2 versus 3.6. Overall, both scenarios score high is this category. While ERS simplifies charging logistics, having modifications in the road might introduce additional risks that would make driving more dangerous. These modifications are also having a potential to cause safety issues when other types of ERS are considered, as they may reduce skid resistance, create uneven surfaces, and raise concerns over lane-changing safety (Speth & Funke, 2021; PIARC, 2018; Cheng & Lin, 2024)

Access to Infrastructure

Access to infrastructure is a decisive factor in the operational feasibility of BEHDVs, particularly when comparing static charging systems and ERS. The existing infrastructure for BEV-based operations is technologically mature and increasingly available. Static charging solutions, especially at depots and logistics hubs, are already implemented in several freight operations and can accommodate high-power applications of 350 kW or more (Link & Plötz, 2022). Although public charging stations tailored to the needs of BEHDVs remain limited, national and EU-level strategies have begun addressing this gap, targeting rest areas and key corridors for infrastructure development (Shoman et al., 2022, Cheng & Lin, 2024). As a result, the primary barriers to BEHDV infrastructure deployment are not technological but logistical and regulatory. This indicator from the BEHDV scenario side is evaluated as Moderate Performance.

By contrast, ERS infrastructure remains in the demonstration and early pilot phases. Although countries like Sweden and Germany have conducted field trials, the total network length remains marginal and lacks interoperability standards across borders (PIARC, 2018; Burghard et al., 2024). Despite ERS being a technically promising concept, most forms, whether inductive, rail-based, or overhead, are currently deployed as prototypes, rather than full-fledged solutions. Moreover, large-scale ERS implementation would require substantial investment, long lead times, and alignment across road operators, energy providers, and regulatory bodies (PIARC, 2018, Burghard et al., 2024; Plötz et al., 2024). Current planning documents acknowledge that ERS will likely only be deployed on strategic freight corridors in the foreseeable future, requiring hybrid vehicles to rely on conventional static charging infrastructure when operating off-network (Shoman et al, 2022).

Infrastructure Assessment is provided in the Table 4.13. BEHDV-only scenario significantly outperforms ERS-enabled scenario (average score of 3.33 compared to 1) due to already established charging standards, existing geographical coverage and maturity of the charging technology.

Table 4.13: Infrastructure Assessment for BEHDV and BEHDV with ERS scenarios.

Dimension	BEHDV	BEHDV + ERS	Reference
Infrastructure Maturity	**Moderate Performance.** Charging using Combined Charging Systems (CCS) is already commercial (TRL 9), Megawatt Charging System (MCS) still not commercially deployed (TRL 7-8).	**Very Low Performance.** Overhead conductive system TRL 7-8 (pilot-tested in Germany, Sweden) but it needs further large-scale testing.	Link & Plötz (2022); Shoman et al. (2023); Schulte & Ny (2018); Interview with Stakeholder Expert 10 (A.10), Stakeholder Expert 2 (A.2); Stakeholder Expert 4 (A.4)
Geographical Coverage	**Low Performance**. Static chargers create reliable islands, yet public corridor coverage is still patchy. Existing sites are sized for passenger cars, so they are not offering the charging for larger vehicles.	**Very Low Performance**. ERS infrastructure is still limited to pilot projects in countries like Sweden and Germany. No country has deployed a continuous or nationally integrated ERS network. Planned deployment is restricted to select high-traffic corridors, and full cross-border operability remains lacking.	Shoman et al. (2023); Plötz et al. (2024); Cheng & Lin (2024); Sugihara et al. (2023)
Interoperability and Standardization	**High Performance**. Static charging systems (e.g. CCS) are already widely	**Very Low Performance**. ERS requires harmonization of various hardware interfaces (e.g.,	Plötz et al. (2024); PIARC (2018); Interview with

	standardized and allow for cross-manufacturer and cross-border interoperability. The emerging MCS standard is also being developed with coordination among major stakeholders.	pantograph, current collectors). Lack of EU-wide standardization across ERS technologies (overhead, inductive, conductive) constrains interoperability and scalability	Stakeholder Expert 2 (A.2), Stakeholder Expert 3 (A.5), Stakeholder Expert 7 (A.7)

Shippers

Cost Efficiency (Freight Rates)

Cost efficiency for shippers refers to the ability to secure competitively priced transport services that account for both the operational costs of the carrier or freight forwarder and the actual volume of goods moved. The relevant indicator is the cost per tonne-kilometer (EUR/tkm), which reflects how much a shipper effectively pays per tonne of cargo transported over one kilometre.

To isolate the impact of different vehicle configurations on transport cost, this indicator is derived from the carrier's TCO per kilometer, adjusted by the net payload capacity of the vehicle. The study uses the carrier's total cost of ownership TCO per kilometre as the basis for calculating shipper cost efficiency because it reflects the actual operating costs incurred by carrier or freight forwarder, which are directly passed on to shippers through freight rates. Although carriers or freight forwarders typically apply a markup over cost to account for overhead and profit, this analysis assumes that the markup is applied uniformly across both scenarios. As a result, the relative difference in EUR/tkm remains unaffected, and the markup is excluded from the comparative analysis. Furthermore, the full net payload capacity is used for the calculations even though vehicles are not usually loaded completely fully. Similarly to the TCO/km, it is assumed that the vehicle will be loaded filling the same relative share of the net payload thus not changing the relative EUR/tkm outcome.

The TCO/km values are taken directly from the earlier calculations under Total Cost of Ownership (Carriers), while net payload figures are taken from the payload analysis of Vehicle Payload and Weight (Carriers).

Table 4.14: Freight rate per tonne-kilometre calculation for BEHDV and BEHDV with ERS scenarios.

Scenario	Battery Size	Net Payload	TCO/km	EUR/tkm
BEHDV	1111 kWh	20 900 kg	0.629 EUR	0.03 EUR
BEHDV + ERS	389 kWh	23 365 kg	0.651 EUR	0.028 EUR

As summarized in the Table 4.14, when vehicle payload is taken into account, the BEHDV + ERS scenario is better by a small margin. In the ERS scenario, the ability to carry more freight per trip is offset by the higher TCO, leading to an almost exactly the same EUR/tkm as in static charging only scenario.

Sustainability / CO2 Emissions Reduction

This criterion evaluates the potential of transport operations to support corporate sustainability targets and emissions reporting obligations. As shippers typically report on CO_2 emissions using tank-to-wheel metric, tailpipe CO_2 emissions will be used to calculate this criterion (Raoofi et al, 2025).

BEHDVs, whether operating in a battery-only configuration or via ERS, produce zero tailpipe emissions (Bhardwaj & Mostofi, 2022; Taljegard et al., 2020). Since both transition pathways achieve the same performance in terms of tailpipe emissions, we assume equal effectiveness under this criterion. It is important to note that this approach is limited to focus on the shipper perspective. Full analysis on the related CO_2 emissions would include emissions that were generated during vehicle and infrastructure development and manufacturing.

Reliability of Delivery Schedules

This criterion is similar to the Operational Reliability from the carrier side, but it does not focus on the charging time. Shippers only care whether the goods are being picked up and dropped off on time, while the disruptions in between these points are irrelevant. If the charging and detours are anticipated and integrated into route planning, the carrier can make it to the next stop on time without causing issues for the shipper. Due to these reasons, a qualitative Operational Reliability Impact Assessment is used and presented in the Table 4.15.

Table 4.15: Reliability of Delivery Schedules for BEHDV and BEHDV with ERS scenarios.

Factor	BEHDV	BEHDV + ERS	Reference
Queueing / Charging Uncertainty	**Low Performance.** BEHDVs depend on public charging hubs that often lack booking systems and consistent power delivery.	**High Performance.** ERS avoids any queuing because of the charging as long as route is planned on the ERS covered road.	Interview with Stakeholder Expert 1 (A.1), Stakeholder Expert 10 (A.10)
Route Flexibility	**Moderate Performance**. Vehicles can be dispatched across a wide range of routes. Flexibility is constrained mainly by battery range and charger availability.	**Very Low Performance**. Route choice is limited to ERS corridors. Off-corridor deployment requires larger battery use, undermining the ERS advantage.	Speth & Funke (2021); Shoman et al, (2022); Interview with Stakeholder Expert 10 (A.10)
Charging-Induced Operational Disruption	**Low Performance**. 16-32% increase in journey time compared to diesel vehicles. BEHDVs are limited to the battery capacity as there are no fast-charging options that can be incorporated into mandatory driver breaks.	**Moderate Performance**. 10-20% increase in extra distance required to driver to reach ERS-enabled roads. ERS availability is still essential, but the vehicle doesn't encounter distance limitations.	Chen & Lin (2023); Bakker et al. (2024); Operational Reliability carrier criteria.

From the shipper's perspective, both BEHDV-only and ERS-supported configurations score similarly on Operational Reliability Impact Assessment with BEHDV + ERS scoring 2.67 in comparison to 2.33. While ERS eliminates charging-related queueing and removes the daily vehicle distance limitation, the BEHDVs offer greater route flexibility and easier rerouting.

Well-being of Drivers

While shippers do not manage drivers directly, many prioritize subcontractor well-being and reliability in delivery execution. Since this factor was assessed in detail under the carrier criteria, the same qualitative evaluation applies here. As concluded there, ERS-supported scenario performs higher compared to BEHDV-only one by 4.2 to 3.6 average score.

Vehicle Manufacturers

Profitability and Customer Demand

Profitability and Customer Demand refers to the ability of truck manufacturers to design, produce, and sell BEHDVs that meet market expectations and generate sufficient return on investment. In the static charging scenario, profitability prospects are considered moderate to high. Qualitative Profitability and Demand Assessment will be used as an indicator for this criterion.

Studies project that BEHDVs could reach TCO parity with diesel trucks by around 2027, especially as battery prices decline and operational costs drop (Raoofi et al., 2025). Manufacturers are trying to respond to regulatory and customer pressure by scaling up BEHDV production, though doing so still requires significant upfront investment. As Stakeholder Expert 9 noted, that the transition to BEHDVs requires substantial investment, and manufacturers need to see clear demand before committing resources. At the same time, BEHDV demand is expected to grow as more shippers and carriers seek low-emission transport solutions, and as charging infrastructure becomes more accessible.

In the BEHDV with ERS scenario, profitability is more constrained. While ERS could enable smaller batteries and reduce vehicle costs, this may in fact be commercially less attractive to manufacturers. As Stakeholder Expert 4 pointed out, smaller batteries mean lower truck prices and potentially reduced revenues. Carrier (customer) demand for ERS-compatible trucks is also extremely limited, with most carriers hesitant to invest in such vehicles in the absence of widespread and reliable infrastructure (Interviews with Stakeholder Expert 3, A.3; Stakeholder Expert 7, A.7). As a result, both profitability and customer demand under the ERS scenario remain low, despite the long-term theoretical benefits.

Table 4.16: Profitability and Customer Demand for BEHDV and BEHDV with ERS scenarios.

Dimension	BEHDV	BEHDV + ERS
Manufacturer Profitability	**Moderate Performance**. BEHDVs are expected to reach TCO parity with diesel around 2027. OEMs are scaling production, but high R&D investments are still required.	**Low Performance**. Smaller batteries enabled by ERS may reduce vehicle prices and vehicle manufacturer revenue. Some manufacturers view this as commercially unattractive.
Customer Demand	**Moderate Performance**. Driven by regulatory pressure and improved charging infrastructure.	**Very Low Performance**. Carriers hesitate to invest in ERS-compatible trucks without reliable infrastructure; demand remains speculative.

Profitability and Demand Assessment summary is presented in the table 4.16. Overall, while BEHDVs present a commercially viable pathway for manufacturers with growing market demand and long-term profitability potential, the ERS-based approach remains less attractive in the near term due to limited demand and the risk of reduced revenue from lower vehicle pricing (average scores of 3 and 1.5 respectively).

Standardization and Interoperability

Standardization and interoperability refer to the extent to which truck manufacturers must align with external hardware and system standards when developing BEHDVs. In the BEHDV-only scenario, this need is relatively low. Static charging technologies have already reached a high degree of standardization, enabling interoperability across networks and granting manufacturers the flexibility to differentiate their vehicle designs (Stakeholder Expert 2, A.2). In contrast, the BEHDV + ERS scenario involves a high need for standardization. ERS systems rely on hardware components like pantograph interfaces and current collectors, which must be harmonized across vehicle types and countries. This requirement may constrain vehicle manufacturers innovation and increase the risk of stranded investments. As noted in the literature, "ERS systems require a high level of vehicle standardization - particularly around pantograph interfaces and current collector technology - which may limit OEMs' ability to differentiate and innovate vehicle designs" (Speth & Funke, 2021). The issue was also mentioned in the expert interviews, where multiple industry experts emphasized that manufacturers are hesitant to commit to ERS-compatible vehicle production without broader infrastructure deployment and clear standards (Interview with Stakeholder Expert 3, A.5; Stakeholder Expert 7. A.7).

As a quantitative indicator, charging TRL is used. It was already discussed in the Infrastructure Maturity dimension of the Access to Infrastructure carrier criteria:

- CCS static charging is TRL 9.
- Overhead conductive ERS is TRL 7-8.

Therefore, from the standardization and interoperability perspective, BEHDV-only scenario is preferred from the vehicle manufacturer perspective.

Infrastructure Readiness

Infrastructure Readiness refers to the extent to which the supporting charging systems - static for BEHDVs and dynamic for ERS - are technologically mature, widely deployed, and capable of enabling reliable and large-scale operations for BEHDVs. BEHDVs charging infrastructure is advancing along three dimensions: technological maturity (TRL), scalability, and deployment. Charging using CCS is already commercial (TRL 9), while MCS for long-haul use is catching up but not yet at full commercial deployment. Scalability is strongest for depot charging, given its integration into existing logistics hubs and resting locations, while public MCS networks face layout, cost, and power constraints. Deployment is progressing, particularly in countries like Germany and Belgium, but remains uneven due to grid and permitting limitations. By contrast, ERS vary more widely in maturity: overhead conductive systems are technically proven, but inductive and rail-based variants are less mature and face greater scalability and deployment barriers. A structured summary of this criteria is presented in the Table 4.17.

Table 4.17: Infrastructure Readiness for BEHDV and BEHDV with ERS.

Dimension	BEHDV	BEHDV + ERS	References
Technology Readiness Level (TRL)	CCS: TRL 9. MCS: TRL 7-8; 720 kW-1 MW systems expected by 2030 but not yet field-proven at scale.	Overhead conductive systems: TRL 7-8 (pilot-tested in Germany, Sweden). Inductive & rail-based conductive: TRL 3-7, facing energy and integration issues.	Link & Plötz (2022); Shoman et al. (2023); Schulte & Ny (2018); Interview with Stakeholder Expert 10 (A.10), Stakeholder Expert 2 (A.2); Stakeholder Expert 4 (A.4)
Scalability	**High Performance** for depot CCS, due to integration into logistics hubs and incremental rollout. MCS faces constraints from cost, land, and power limitations.	**Low Performance** due to corridor-specific investment, long lead times, and high capital costs. Flexibility is limited versus modular charging.	Shoman et al. (2022) Interview with Stakeholder Expert 3 (A.5); Stakeholder Expert 1 (A.1); Stakeholder Expert 4 (A.4); Stakeholder Expert 8 (A.8)
Deployment Status	**High Performance**. Widespread for CCS, particularly in Germany & Belgium. MCS still in early-phase rollouts.	**Very Low Performance**. Limited to pilot corridors (e.g., 2-5 km test tracks). Broader rollout faces challenges in standardization, interoperability, and grid integration.	Shoman et al. (2023); Link & Plötz (2022); Taljegard et al. (2020); Interview with Stakeholder Expert 9 (A.9); Stakeholder Expert 2 (A.2)

Since this is a mix of qualitative and quantitative indicators, Infrastructure Readiness Index will be used as an indicator:

$$IRI = \frac{w_1 \cdot TRL + w_2 \cdot Scalability\ score + w_3 \cdot Deployment\ Score}{w_1 + w_2 + w_3}$$

As it is hard to estimate the weight of these dimension correctly, it is assumed that they are equal between the dimensions. Furthermore, as TRL is the most critical dimension (without maximum TRL, scalability and deployment are not possible), the TRL number will be used in the equation. For the other two dimensions, Likert-type scores will be used as in other qualitative indicators.

Table 5.18: Infrastructure Readiness Score summary for both scenarios.

Scenario	TRL	Scalability	Deployment	Infrastructure Readiness Index
BEHDV	9	4	4	5.67
BEHDV + ERS	7	2	1	3.33

The calculated Infrastructure Readiness Index in the Table 5.18 highlights a clear advantage for the BEHDV scenario over the ERS-supported alternative. With an IRI of 5.67, BEHDVs benefit from mature technology (TRL 9), high scalability due to static charging integration, and a relatively widespread deployment. In contrast, the ERS scenario scores significantly lower, with an IRI of 3.33, reflecting its lower technological maturity (TRL 7), limited scalability due to corridor-specific implementation, and minimal real-world deployment to date. These results indicate that, from vehicle manufacturer perspective, BEHDVs are substantially more viable for near-term adoption.

Long-Term Technology Risk

Long-term technology risk refers to the likelihood that a chosen vehicle and charging technology will become obsolete or misaligned with future infrastructure, regulatory, or market developments. In the BEHDV-only scenario, this risk is assessed as low. BEHDVs build on mature and widely deployed charging technologies that have evolved from the passenger vehicle sector. Plug-based systems such as CCS are already established and undergoing scaling and adaptation for heavy-duty use. While some formal industrial standards for trucks are still under development, the direction of travel is clear and incremental, lowering the risk of technological redundancy.

In contrast, the BEHDV + ERS scenario presents a high long-term technology risk. The ERS ecosystem involves multiple competing technologies, each with different requirements and implications for vehicle design. The maturity and standardization of the technologies differ significantly and ERS technologies are still in early deployment stages, mostly at the demonstration level. This fragmentation increases the uncertainty for vehicle manufacturers. Manufacturers are hesitant to invest heavily in ERS-compatible vehicles without a clear signal on which ERS technology will prevail or be supported at scale. This concern is also mentioned by Stakeholder Expert 2, who stated that investing heavily in ERS-compatible vehicles is risky if the infrastructure isn't widely adopted or if another disruptive technology takes over within a few years.

To create an indicator for this criterion, the Gartner-style Hype Cycle framework is used as a qualitative tool to indicate a technology's position along the innovation maturity curve. The Hype Cycle characterizes the typical lifecycle of emerging technologies through five stages: innovation trigger, peak of inflated expectations, trough of disillusionment, slope of enlightenment, and plateau of productivity (Figure 4.9; Fenn & Raskino, 2008). Technologies positioned earlier in the cycle are generally associated with higher uncertainty, fragmented development paths, and elevated risk of obsolescence or strategic misalignment. Conversely, technologies approaching or residing on the plateau of productivity are considered mature, stable, and less vulnerable to disruptive shifts. By situating BEHDVs and ERS technologies along this curve based on their technological maturity, deployment status, and stakeholder perceptions, the relative long-term risk of each adoption pathway can be inferred. Score of 1 is assigned to innovation trigger as it is the riskiest stage while score of 5 is assigned to plateau of productivity at which technologies are mature with the least amount of risk. Higher score indicates a better performance for the scenario.

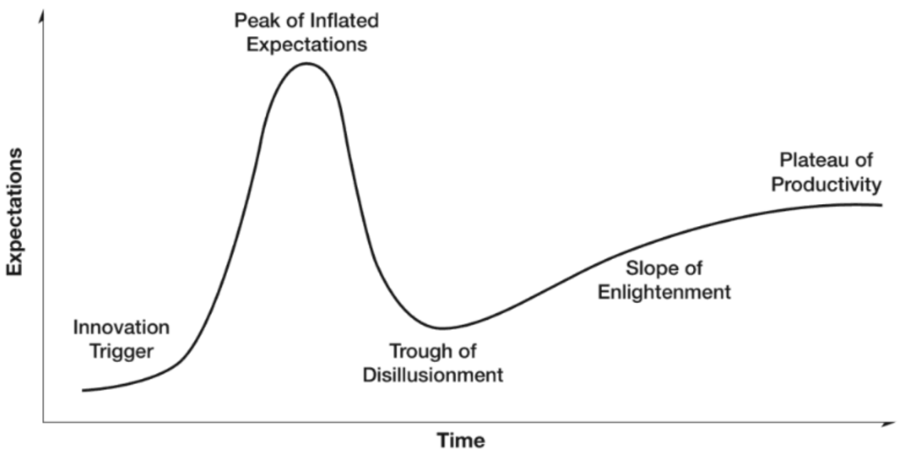

Figure 4.9: Gartner hype curve (Fenn & Raskino, 2008).

BEHDVs are positioned on the Slope of Enlightenment on the Hype Cycle. The technology is mature, widely supported by OEMs, and increasingly integrated into regulatory frameworks such as Alternative Fuels Infrastructure Regulation (AFIR). Charging infrastructure is expanding, and operational limitations are being progressively addressed. This trajectory indicates low long-term risk, with BEHDVs benefiting from technological stability and growing market acceptance. Therefore, it scores 4 for this indicator. Meanwhile, ERS technologies remain between the Peak of Inflated Expectations and the Trough of Disillusionment. While pilot projects have demonstrated feasibility, competing designs, limited deployment, and lack of standardization contribute to high uncertainty. Stakeholders remain cautious due to unclear policy support and infrastructure scalability, indicating a high long-term technology risk at this stage. BEHDV + ERS scenario scores 2.5.

Electrical Grid Operators

Distributed Load Management

Distributed load management refers to the ability of a charging system to spread electricity demand in time and space to avoid local grid bottlenecks and support overall grid stability.

In a BEHDV-only scenario relying exclusively on static charging infrastructure, electricity demand tends to be concentrated at specific times and locations. This is particularly evident during evening hours, when BEHDVs return to depots or stay in overnight stops and begin charging the battery. Such temporal clustering leads to load peaks, which in turn increase the risk of local grid congestion. The issue is especially pronounced in areas with high vehicle density, such as urban depots or highway rest stops (Friesen et al., 2024).

By contrast, ERS offer a more favourable profile for distributed load management. The ERS-enabled scenario results in the spatial and temporal distribution of electricity demand across extended sections of the road network. This continuous and decentralized energy draw significantly reduces the likelihood of demand peaks at individual nodes (Friesen et al., 2024). Furthermore, dynamic charging not only mitigates stress on local grid infrastructure but also aligns more naturally with the availability of renewable energy sources. Because ERS vehicles typically charge during daytime operation, their load patterns coincide with solar energy generation peaks, enabling better temporal integration of renewables into the grid (Shoman et al., 2022).

According to Likert-type scoring system defined in the Table 4.9, BEHDV-only scenario scores 2 for Low Performance while BEHDV + ERS scenario scores 4 for High Performance in the qualitative distributed load management assessment.

Demand Density

Demand density refers to the anticipated and geographically concentrated electricity demand required to economically justify investments in grid infrastructure. For grid operators, higher demand density enhances infrastructure efficiency by improving the utilisation of substations, feeders, and load management systems. This not only increases the return on network investments but also reduces the need for widespread reinforcements across the distribution grid. This criterion is closely related to previously discussed Distributed Load Management, but in this case the focus is on coverage of physical infrastructure.

In scenarios where BEHDVs rely solely on static charging, electricity demand is dispersed across thousands of individual depots, rest stops, and delivery locations. While this decentralised model offers flexibility and allows for incremental deployment, it typically results in fragmented demand patterns. This dispersion undermines economies of scale and raises the cost per megawatt delivered, making infrastructure investments less attractive from a grid operator’s perspective.

In contrast, ERS concentrate energy delivery along high-traffic freight corridors, often overlapping with national motorways and core logistics routes. Studies conducted in Sweden have shown that electrifying just 4% of the national road network could accommodate more than 50% of total freight traffic, leading to an exceptionally high ratio of electricity demand per kilometre of infrastructure (Shoman et al., 2022). This spatial concentration of demand facilitates more efficient use of grid assets and allows for centralised reinforcement at fewer, strategically chosen locations. According to simulation models, ERS infrastructure becomes economically viable on routes exceeding 2,000 trucks per day, where high and predictable utilisation supports favourable returns on investment for both public and private stakeholders (Deshpande et al., 2023).

From the perspective of grid operators, the BEHDV + ERS configuration demonstrates significantly stronger performance in terms of demand density and network-side infrastructure return. Although the initial capital expenditure is higher, the return on network assets improves with each additional vehicle on the ERS network, in contrast to the diminishing returns observed in static charging scenarios. This scenario scores 5 with Very High Performance while BEHDV-only - 2 points with Low Performance.

Grid Capacity Constraints

The absolute ability of the grid to accommodate the increased demand plays a critical role in the deployment of electrified freight systems. In static charging scenarios, decentralised charging often results in uneven usage patterns and localised peak loads, particularly during evening hours when vehicles return to base. These concentrated peaks place significant pressure on local grid nodes, often requiring costly upgrades to substations and transformers with relatively low utilisation rates (Shoman et al., 2022). As noted by Stakeholder Expert 8 (A.8), such reinforcement needs in densely populated or already constrained areas may also trigger community opposition, further complicating grid planning.

ERS systems mitigate many of these challenges by enabling in-motion charging during midday hours, which better aligns with solar energy production and underutilised daytime grid capacity. In Germany, midday electricity prices have already fallen by approximately 0.06 EUR per kilowatt-hour due to solar surplus, indicating available capacity during these periods (Interview with Stakeholder Expert 8, A.8). The predictable and continuous nature of ERS power flows also improves substation utilisation, as energy is drawn steadily rather than in short, high-load intervals. As Rogstadius (2023) highlights, this sustained and concentrated load facilitates more efficient planning and reduces uncertainty in grid upgrades.

Additionally, ERS allows for reinforcement to be concentrated in fewer, high-traffic corridors, as opposed to widespread grid upgrades across the country. This centralisation reduces the scale and cost of grid interventions and enables more strategic infrastructure planning. As Deshpande et al. (2023) argue, this makes ERS a more grid-compatible solution in terms of reinforcement feasibility and long-term scalability.

To quantify and compare this indicator, Grid Capacity Constraints Assessment is calculated in the Table 4.19. The ERS-enable scenario outperforms static charging (scoring 4 versus 2.33) one due to more predictable electricity demand and reduced peak hour stress on the grid.

Table 4.19: Grid Capacity Constraints Assessment for BEHDV and BEHDV with ERS scenarios.

Dimension	BEHDV	BEHDV + ERS	Reference
Peak-load stress	**Low Performance.** Static charging peaks during the evenings. In case MCS, the impact would be even higher.	**Very High Performance.** Daytime corridor use aligned with solar supply.	Shoman et al. (2022); Interview with Stakeholder Expert 8 (A.8)

Substation utilisation	**Moderate Performance**. Variable asset utilisation.	**High Performance**. Sustained, predictable utilisation.	Rogstadius (2023)
Grid-reinforcement requirement	**Low Performance**. Upgrades needed across wide geography	**Moderate Performance**. Centralised upgrades in high-traffic corridors.	Deshpande et al. (2023); Interview with Stakeholder Expert 8 (A.8)

Policy Stability and Regulatory Support

This criterion evaluates the extent to which existing policy frameworks offer long-term regulatory certainty for grid operators investing in charging infrastructure for BEHDVs. The comparison reflects key differences in how static charging and ERS are addressed in EU policy instruments and national strategies.

To quantify this evaluation, analysis on Policy Horizon Certainty and Grid Investment Eligibility is made. The summary is presented in the Table 4.20. BEHDV-only scenario significantly outperforms ERS one by an average score of 4.5 to 2 due to significantly more mature existing regulatory frameworks.

Table 4.20: Policy Stability and Regulatory Support Assessment for BEHDV and BEHDV with ERS scenarios.

Dimensions	BEHDV	BEHDV + ERS	References
Policy Horizon Certainty	**High Performance**. Static charging is backed by AFIR and national long-term transport decarbonization plans.	**Low Performance**. ERS is mentioned but lacks detailed timelines in major policy frameworks	European Commission, (2019); Plötz et al. (2024); Friesen et al. (2024)
Grid Investment Eligibility	**Very High Performance**. Static charging grid connections are typically eligible for EU and national subsidies (e.g., CEF, AFIR).	**Low Performance**. ERS-related upgrades often fall outside reimbursement schemes	Friesen et al. (2024); Interview with Stakeholder Expert 1 (A.1)

Road Operators

Investment and Maintenance Needs

For road operators, investment and maintenance refer to the upfront capital expenditures required for installing new charging infrastructure and the recurring costs for upkeep. These costs are critical for assessing the long-term economic feasibility of static charging for BEHDVs and ERS.

BEHDVs rely on static charging infrastructure such as depot-based and public fast chargers. These installations do not require modification of the road itself, meaning lower direct involvement from road operators. Instead, costs are concentrated in site-level investments and maintenance. On the other side, ERS infrastructure - such as catenary overhead lines - requires direct integration into roadways, including poles, wiring, and power systems. These systems entail much higher upfront and maintenance costs but can support a large fleet with high utilization. The Table 5.21 reflects the annualized infrastructure cost per kilometer in both cases. To assess infrastructure efficiency, this indicator calculates the annualized cost per kilometer of truck movement supported by each station. Calculations are made on the basis on study by Speth and Funke (2021).

Table 4.21: Comparison between annualized cost between scenarios (Speth & Funke, 2021).

Component	BEHDV	BEHDV + ERS
Investment (CapEx)	1 176 000 EUR	3 421 000 000 EUR
Lifetime	30 years	30 years
Annualized CapEx	39 200 EUR	114 033 333 EUR
OpEx	24 000 EUR	68 420 000 EUR
Total Annual Cost (CapEx + OpEx)	63 200 EUR	182 453 333 EUR
Number of vehicles on infrastructure	7	61 875
Annual vehicle kilometres travelled by one vehicle on infrastructure	120 000 km	61 900 km
Total annual vehicle kilometers travelled on infrastructure	840 000 km	3 830 062 500 km
Annualized Cost	0.072 EUR/km	0.048 EUR/km

While static charging infrastructure has lower upfront demands and greater flexibility, ERS scenario - despite significantly higher investment need - offer lower cost per kilometer when deployed at scale and with high utilization.

Land Use Efficiency

Land use efficiency refers to the extent to which each infrastructure solution minimizes the need for additional land acquisition and optimally integrates with existing transport corridors. For road operators and planners, this indicator is vital in assessing the physical footprint, disruption to land use patterns, and potential implications for zoning and road capacity.

BEHDVs using depot or public fast-charging infrastructure require the development of physical sites dedicated to vehicle charging. These sites must accommodate not only the charging hardware but also the necessary vehicle manoeuvring and parking space, power electronics, and often buffer zones for safety. According to Zähringer et al. (2024), effective charging infrastructure for long-haul BEHDVs requires an average of one high-power charger every 50 km to keep additional time losses under 30 minutes per day. This assumes a distributed charging power of 700-1500 kW and a charger availability above 75%, emphasizing the need for dense and highly reliable charging networks to maintain operational performance (Zähringer et al., 2024). High charger density and availability suggest that dedicated land for hubs and supporting infrastructure may be significant. Furthermore, the real-world constraints such as parking space limitations and available grid capacity are often overlooked in theoretical infrastructure models. Analysis shows that at a 15% electrification rate, roughly 17% of truck parking lots at each location would need to be converted into charging zones - indicating a substantial spatial demand even at moderate adoption levels (Speth et al., 2025). Additionally, charging infrastructure development for heavy-duty trucks is significantly more complex than for passenger vehicles due to higher power and energy demands. High-capacity fast charging stations require not only grid upgrades but also considerable physical space and construction delays, reinforcing the point that land use efficiency becomes a key constraint in public charging expansion (Raoofi et al., 2025).

On the other hand, ERS demonstrate high land-use efficiency by largely utilizing the existing motorway corridor without the need for significant additional land acquisition. The typical configuration for overhead conductive ERS includes masts positioned on the road verge approximately every 60 meters, supporting power lines situated around five meters above the road. Technical components such as rectifier stations, required every two kilometers, are compact and comparable in size to a standard sea container. As shown in the Dutch cost-effectiveness study, these installations remain within the highway's existing right-of-way, minimizing disruption to adjacent land uses (Decisio, 2022; Coban et al., 2022). From a spatial planning perspective, this integration avoids the large land footprint associated with static fast-charging hubs, which demand extensive physical space for vehicle manoeuvring and buffer zones. Furthermore, life-cycle assessments caution that natural land transformation remains a critical environmental impact category for ERS infrastructure, particularly due to potential interference with productive land use, deforestation, and habitat fragmentation (Schulte & Ny, 2018). Thus, while ERS solutions are spatially efficient, their long-term ecological impacts must be evaluated alongside visual and social considerations.

As an indicator for this criteria, Land Use Intensity (LUI) is used:

$$LUI = \frac{Total\ Additional\ Land\ Area\ (m^2)}{Electrified\ Corridor\ Lenght\ (km)}$$

It is assumed that vehicle throughput and charging powered delivered is the same for both scenarios even though ERS scenario require less total power due to reduced weight of the vehicle. The summary of this indicator is provided in the Table 4.22. BEHDV + ERS scenario requires around 10 times less land area, so it significantly outperforms the static charging only one.

Table 4.22: Land Use Intensity comparison for BEHDV-only and BEHDV + ERS scenarios.

Scenario	Land Use	Land Use Intensity	References
BEHDV	Each charging hub (incl. manoeuvring, parking, buffer) 2,500-5,000 m² per location every 50 km	50-100 m²/km	Zähringer et al. (2024); Speth et al. (2025); Raoofi et al. (2025)
BEHDV + ERS	Masts every 60 m (no extra land) + rectifier stations (15-20 m² every 2 km)	7.5-10 m²/km	Decisio (2022); Coban et al. (2022); Schulte & Ny (2018)

Public Acceptance and Visual Impact

Social acceptance of charging infrastructure is shaped by its visibility, required public works, and interactions with local permitting and land-use processes. From a visual perspective, stationary fast-charging hubs may appear compact at first glance, but their high-power levels demand bulky grid components - such as fenced transformer yards and tall cooling cabinets - that can trigger localized resistance during siting and permitting (Yu et al., 2024). In contrast, overhead-line ERS introduces a more continuous and conspicuous presence along motorways, with steel poles, gantries, and contact wires installed every 50 to 60 meters. While these installations remain largely within the existing road corridor, their cumulative visual impact and proximity to private property increase the complexity of stakeholder negotiations (Friesen et al., 2024).

Regarding public works fatigue, the stationary charging approach involves concentrated but highly disruptive upgrades at each truck stop. These include new substations and transformer installations, with modelling suggesting that even moderate adoption levels - such as 15% BEHDV penetration - require large investments at each location, often delayed by slow grid connection timelines (Shoman et al., 2023; Speth et al., 2025). While ERS infrastructure benefits from linear integration along motorways, the sheer scale of the rollout - potentially spanning thousands of kilometers - results in prolonged construction periods visible to a broader public. Citizens and adjacent communities are thus exposed to extended construction zones, which may erode public support over time (Bhardwaj & Mostofi, 2022).

Permitting and zoning processes further complicate social acceptance for both options. Stationary chargers typically retrofit existing rest areas, but grid upgrades for megawatt-scale hubs can trigger renewed zoning debates, especially when additional land or transmission infrastructure is needed (Speth et al., 2025). Meanwhile, ERS faces a more fragmented permitting challenge: each mast, feeder line, and substation require separate approvals, and the involvement of numerous municipalities across the network leads to complex and prolonged negotiations, particularly where aesthetic or environmental concerns are raised (Friesen et al., 2024).

To quantify this indicator, Likert-type scores will be used as in other qualitative indicators. The summary of considered dimensions and their performance can be found in the Table 4.23.

Table 4.23: Criteria related to public acceptance and visual impact comparison for both scenarios.

Dimension	BEHDV	BEHDV + ERS
Visual Footprint & Landscape	**Moderate Performance**. Localized but visually dense at hub sites.	**Low Performance**. Linear and continuous visual impact along motorways for overhead conductive type. Inductive or ground-level conductive types have smaller negative impact.
Scale of Public Works	**Low Performance**. Very disruptive but concentrated at specific locations	**Moderate Performance.** Concentrated per site but extended over large areas.
Permitting & Land-Use Politics	**Moderate Performance**. Retrofit-friendly with some zoning conflicts.	**Low Performance**. Complex, multi-jurisdictional approval process.
Overall Social Acceptance	**Moderate Performance**. Localized resistance manageable with planning.	**Low Performance**. Broader, systemic resistance due to scale and visibility.

BEHDV-only scenario scores an average of 2.75 while ERS - 2.25. In practical terms, stationary charging can often be concealed or co-located on industrial land, making local acceptance problems solvable with good design and stakeholder engagement. ERS must win a broader public conversation about altering the look of national motorways. It is important to note that in case of other ERS technologies (ground-level conductive or inductive), the situation changes drastically as the biggest pain points of BEHDV + ERS scenario, like visual footprint and visibility, become obsolete.

Freight Forwarders

Cost Stability and Control (Energy Costs)

Cost Stability and Control refers to the ability to forecast the most fluctuating cost component of the transport: fuel or energy costs. As mentioned in the literature review, diesel prices can fluctuate up to ±10% month-on-month basis while it accounts for 27-30% of the road transportation price (DKV, 2025; Gonon, 2025).

The key indicator to estimate this criterion is electricity price variability in both scenarios. Energy cost difference between scenarios was already estimated in the TCO carrier criteria and in ERS scenario it's around 10% smaller due to higher vehicles efficiency (smaller weight due to a smaller battery). Furthermore, as stated by Shoman et al. (2022), ERS enables stable daytime electricity usage aligned with solar generation. Secondly, the demand in ERS scenario would be more predictable, thus variability of electricity price should be lower. Moreover, according to Friesen et al. (2024), ERS is expected to be operated under long-term infrastructure contracts with fixed per-kWh rates.

To quantify this indicator Cost Stability Index (CSI) is used:

$$\mathrm{CSI} = \left(1 - \frac{\text{Price Variability}_{\text{ERS}}}{\text{Price Variability}_{\text{BEHDV}}}\right) \times (1 + \text{Efficiency Factor})$$

Due to the reasons mentioned above, it is assumed that ERS scenario has two times smaller price variability as empirical data for ERS electricity price does not exist. The summary of CSI calculations can be found in the Table 4.24. ERS scenario performs better due to the reasons explained earlier.

Table 4.24: Cost Stability Index cancelation for BEHDV and BEHDV with ERS scenarios.

Scenario	Price Variability	Efficiency Factor	CSI Score
BEHDV	10%	0	0
BEHDV + ERS	5%	0.1	0.55

Operational Efficiency

This criterion refers to the planning of the vehicle utilisation while assigning or reassigning it to plan routes. A qualitative assessment of the Operational Efficiency is used taking three factors that were already used while evaluating Flexibility and Asset Utilization carrier criteria. The summary is presented in the Table 4.25.

Table 4.25: Operational Efficiency for BEHDV and BEHDV with ERS.

Dimension	BEHDV	BEHDV + ERS	Reference
Route Flexibility	**Moderate Performance**. Vehicles can be dispatched across a wide range of routes. Flexibility is constrained mainly by battery range and charger availability.	**Very Low Performance**. Route choice is limited to ERS corridors. Off-corridor deployment requires larger battery use, undermining the ERS advantage.	Speth & Funke (2021); Shoman et al, (2022); Interview with Stakeholder Expert 10 (A.10), Stakeholder Expert 9 (A.9)
Asset Reassignment Flexibility	**Moderate Performance**. BEHDV assignments are tied to existing static charging infrastructure, making redeployment logistically somewhat difficult without extensive planning.	**Very Low Performance**. Assignments are fully tied to existing ERS coverage.	Speth & Funke (2021); Cheng & Lin (2024); Shoman et al, (2022); Interview with Stakeholder Expert 4 (A.4)
Flexibility for Cross-Border Operations	**Moderate Performance**. Charging compatibility and vehicle weight restrictions vary between countries, requiring advanced planning and posing operational risks. Payment for electricity usage is a problem.	**Low Performance**. Without international ERS standardization and corridor continuity, vehicles lose the ability to operate beyond national coverage zones.	PIARC (2018); Aronietis & Vanelslander (2024); Interview with Stakeholder Expert 1 (A.1) & Stakeholder Expert 7 (A.7)

From the perspective of operational efficiency of freight forwarders, BEHDV-only is a more favourable scenario (average score 3 versus 1.33) due to higher asset flexibility in multiple dimensions.

Competitive Advantage

This criterion evaluates how each transition pathway can enhance freight forwarders' strategic positioning and market competitiveness. While academic literature is limited, insights from industry initiatives and interviews suggest several pathways through which BEHDVs, with or without ERS, may offer competitive advantage.

Electric trucking is no longer just a sustainability checkbox. As Stakeholder Expert 3 (A.3) notes, freight forwarders like sennder see electrification as a strategic cost advantage, particularly due to greater control over energy pricing. Unlike diesel, electricity costs can be stabilized, especially when paired with renewables or storage, allowing freight forwarders to offer more predictable and competitive pricing to shippers.

Moreover, projects like JUNA, the joint venture between sennder and Scania, demonstrate how new business models (e.g., pay-per-use electric trucks) can help forwarders differentiate themselves in the market by offering zero-emission transport at scale, without requiring carriers to commit to upfront capital investment. This model not only reduces barriers to adoption but positions freight forwarders as innovators solving real logistics pain points.

While ERS-based transport might offer less flexibility in the short term, its potential for long-haul electrification without downtime could further boost service reliability - a valuable trait in B2B logistics. Adoption of ERS, once infrastructure scales, may thus become a competitive lever for high-volume, fixed-route operations.

Electrification enables freight forwarders to gain competitive advantage through cost predictability, access to low-emission contracts, and innovative service models. Both BEVs and ERS offer strong competitive advantage potential. However, BEHDVs provide more immediate and accessible benefits, while the strategic value of ERS is more long-term and depends on future infrastructure rollout. ERS may ultimately enhance differentiation further, particularly for freight forwarders operating along fixed, high-utilization corridors. As both scenarios provide or have a potential to provide competitive advantage for freight forwarding companies, both scenarios score Very Higher Performance (5) for this indicator.

Regulatory Compliance and Sustainability Goals

This criterion evaluates how well each scenario supports freight forwarders in meeting corporate sustainability goals and complying with emissions regulations. The primary focus is on transport-related GHG emissions, particularly those reported under tank-to-wheel standards - consistent with the approach used in the shipper criteria Sustainability / CO2 Emissions Reduction. In addition, this criterion also considers lifecycle emissions, alignment with strategic policy frameworks, and the reputational impact associated with technology choices. Another qualitative assessment is used to compare compliance and sustainability goals in both scenarios with a summary provided in the Table 4.26.

Table 4.26: Regulatory Compliance and Sustainability Goals for BEHDV and BEHDV with ERS.

Factor	BEHDV	BEHDV + ERS	Reference
Tailpipe CO_2 Emissions (Tank-to-Wheel)	**Very High Performance**. Zero emissions, fully compliant with EU tailpipe targets.	**Very High Performance**. Zero emissions, fully compliant with EU tailpipe targets.	Bhardwaj & Mostofi (2022); Taljegard et al. (2020)
Lifecycle CO_2 Emissions	**Moderate Performance.** Higher battery capacity increases material and production-related emissions.	**High Performance.** Smaller batteries reduce embedded emissions and lower the energy consumption.	Plötz et al. (2024); Schulte & Ny (2018)
Regulatory Maturity	**High Performance**. Charging infrastructure and vehicle standards are already included in regulations like AFIR.	**Low Performance**. ERS still lacks widespread policy support and standardization.	Plötz et al. (2024)
Sustainability Signalling (Reputation)	**Very High Performance.** Recognized low-emission choice with existing industry benchmarks.	**Very High Performance.** Innovative and publicly visible commitment to zero-emission tech.	sennder (2023a; 2023b)

Both BEHDV and BEHDV + ERS pathways fully meet regulatory requirements for tailpipe emissions, positioning them as compliant solutions for decarbonizing freight operations. However, ERS offers added advantages in lifecycle emissions due to reduced battery reliance and its forward-looking infrastructure model - despite lower policy maturity. Overall, BEHDV-only is slightly more favourable (4.25 versus 4.00) under this criterion due to significantly more mature and consistent regulatory frameworks.

4.7 Criteria Weight and Indicator Summary

To support the comparative stakeholder evaluation, all criteria weights, corresponding performance indicators and indicator performance have been consolidated and structured in Table 4.27 and Appendix H. Table 4.27 contains the criteria grouped on the stakeholder group they belong to and ordered by weight in descending order. Appendix H offers a different perspective since the criteria are grouped by their theme keeping the same ordering logic. The indicator performance is also indicated by colour coding: green - better performance, red - worse performance, yellow - same performance.

Table 4.27: Criteria grouped by stakeholders, sorted by weight, with their indicators and their result.

Stakeholder	Theme	Criteria	Indicator	Weight	BEHDV	BEHDV + ERS	Desirable Direction
Shippers	Economic	Cost Efficiency (Freight Rates)	Cost per tonne-kilometer	0.461	0.03 EUR	0.028 EUR	Lower
	Operational	Reliability of Delivery Schedules	Operational Reliability Impact Assessment	0.216	2.33	2.67	Higher
	Societal	Sustainability / CO_2 Emissions Reduction	Tank-to-wheel CO_2 emissions	0.209	0 gCO_2/km	0 gCO_2/km	Lower
	Societal	Well-being of Drivers	Driver Experience Rating	0.115	3.6	4.2	Higher
Carriers	Economic	Total Cost of Ownership (TCO)	TCO per kilometer	0.283	0.629 EUR/km	0.651 EUR/km	Lower
	Operational	Access to Infrastructure	Infrastructure Assessment	0.187	3.33	1	Higher
	Operational	Operational Reliability	Prolonged journey time	0.169	16-32%	10-20%	Lower
	Operational	Flexibility and Asset Utilization	Operational Flexibility Assessment	0.153	2.8	1.6	Higher
	Operational	Vehicle Payload and Weight	Payload per weight ratio	0.144	0.52	0.58	Higher
	Societal	Driver Satisfaction	Driver Experience Rating	0.064	3.6	4.2	Higher
Vehicle Manufacturers	Economic	Profitability and Customer Demand	Profitability and Demand Assessment	0.495	3	1.5	Higher
	Operational	Infrastructure Readiness	Infrastructure Readiness Index	0.22	5.67	3.33	Higher
	Operational	Standardization and Interoperability	Technology Readiness Level	0.171	9	7-8	Higher
	Operational	Long-Term Technology Risk	Technology Lifecycle Risk Mapping	0.114	4	2.5	Higher
Electrical Grid Operators	Operational	Grid Capacity Constraints	Grid Capacity Constraints Assessment	0.371	2.33	4	Higher
	Societal	Policy Stability and Regulatory Support	Policy Stability and Regulatory Support Assessment	0.306	4.5	2	Higher
	Economic	Demand Density	Demand Density Assessment	0.18	2	5	Higher
	Operational	Distributed Load Management	Distributed Load Management Assessment	0.144	2	4	Higher
Road Operators	Economic	Investment and Maintenance Needs	Annualized infrastructure cost per kilometer	0.471	0.072 EUR/km	0.048 EUR/km	Lower
	Operational	Land Use Efficiency	Land Use Intensity	0.385	50-100 m^2/km	7.5-10 m^2/km	Lower
	Societal	Public Acceptance and Visual Impact	Public Acceptance and Visual Impact Assessment	0.145	2.75	2.25	Higher
Freight Forwarders	Operational	Operational Efficiency	Operational Efficiency Assessment	0.376	3	1.33	Higher
	Societal	Regulatory Compliance and Sustainability Goals	Competitive Advantage Assessment	0.308	5	5	Higher
	Economic	Cost Stability and Control (Energy Costs)	Cost Stability Index	0.169	0	0.55	Higher
	Economic	Competitive Advantage	Regulatory and Sustainability Assessment	0.147	4.25	4	Higher

Stakeholder Perspective

The comparative analysis visualised in Table 4.27 revealed that both scenarios - BEHDVs with static charging only and BEHDVs with ERS integration - offer tangible benefits, but their value varies significantly depending on the stakeholder perspective. From the shipper side, CO_2 emissions and cost (the most important criteria by a significant margin) seems to be the same in both scenarios, while the other two criteria, schedule reliability and driver well-being, are better when ERS network is integrated as complimentary technology next to BEHDVs. Meanwhile, carriers have a strong preference for BEHDV-only scenario as the estimated TCO is around 5% lower while it is the most important criteria of this stakeholder group. The preference is highlighted by better access to infrastructure and versatility of the asset (vehicle) utilisation. Although, ERS-enabled scenario is better in terms amount of excess time spent on routing the vehicle via electrified corridors, payload, and driver experience. Furthermore, vehicle manufacturers have a very strong preference for BEHDV-only scenario as it is favoured in every criterion. The dynamic charging technology is simply too underdeveloped right now in terms of technology, regulation, and availability. Other the other hand, electrical grid operators have a strong preference for the scenario where vehicles can be changed dynamically. In this scenario, network capacity planning is easier, and the electricity demand has smaller deviations that helps to balance the gird. The only drawback, as in the vehicle manufacturer perspective, is the absence of policy and regulatory support. Similarly to electrical grid operators, road operators have a strong preference for ERS-enabled scenario as the criteria that combined 85% of the weight as in favour of it. In this scenario, the investment needs in relative terms are smaller and it requires 10 times less land compared to static charging scenario. It is important to note, that investment needs were calculated if the road utilisation would be high and ERS network development would require significant upfront investment. Lastly, freight forwarders had a small preference for static-charging-only scenario, most due to the operational efficiency due to higher asset flexibility.

Thematic Analysis

When grouped by theme, as discussed in the Cross-Criteria Thematic Analysis section and displayed in the Figure 4.8 and Appendix H, economic and business viability emerged as the most important decision-making factor group across all stakeholders. BEHDV-only scenario performs strongly here, as they align with existing business models, infrastructure maturity, and offers lower TCO for the carriers. ERS-enabled scenario performs better only from road operator and electrical grid operator perspective but, with the same assumptions as mentioned in the previous paragraph, if the ERS corridor utilisation is high. Furthermore, from the operational and technical performance perspective the results are mixed with a slight preference towards the dynamic charging scenario. As some of the criteria indicators can be affected by improving and testing either static or dynamic charging technologies or aligning operational logistics planning with the system limitations, one of the most important criteria in this them cannot. Static charging scenario requires significantly more land and is not suitable for countries like the Netherlands and Germany, as physically there is very limited space for truck charging location expansion or building of new ones. In such countries, electrification of heavy-duty vehicles will be considerably more complex. Lastly, even societal and environmental considerations had the smallest weight from all themes, their consideration is also important to pave way for the successful adoption of these technologies. The more preferred option from this perspective is BEHDV-only scenario but there are a few considerations to keep in mind. The regulatory frameworks and standards for dynamic charging are still developing and they have a reasonable impact on this score. If inductive charging type would emerge as the dominant ERS technology, the negative impact on visual aspect of the road would change in favour of ERS scenario.

4.8 Normalisation and Stakeholder-Weighted Scenario Evaluation

To make the two transition pathways directly comparable across all stakeholder-defined criteria, the performance indicators were first transformed into a common scale. This was necessary because the criteria differ in both units and magnitude - for example, from monetary values (EUR/km) and physical measures (m²/km) to percentages and qualitative ratings. Without such transformation, meaningful aggregation would not be possible.

In this research, 25 criteria were identified from stakeholder interviews, grouped into three thematic dimensions: economic, technical & operational, and societal & environmental. Each was assigned a measurable indicator. These raw values were normalised using a Min-Max approach, a widely applied method in MCDA and particularly suitable for MAMCA applications (Malefaki et al., 2025). In this method, the better-performing alternative on a given criterion is assigned a score of 1, and the poorer-performing alternative a score of 0.

While this binary approach is simple and transparent, it can overstate small differences. For example, when both scenarios perform similarly - such as in TCO per kilometre or Public Acceptance and Visual Impact - assigning one scenario a 1 and the other a 0 may exaggerate the practical significance of the gap. To address this, an indifference threshold was introduced:

- For qualitative and Likert-type indicators, a fixed tolerance of 0.5 points (on a 1-5 scale) was applied.
- For quantitative indicators, a relative threshold of 10% of the average value between the two scenarios was used.

If the performance difference fell within the threshold, both scenarios received an intermediate score of 0.5. Only when the gap exceeded the threshold was the full 0-1 scale applied. This adjustment reduces distortion and better reflects real-world decision-making.

Once the indicators were normalised, the stakeholder-specific BWM weights were applied. This multiplication links actual performance to stakeholder priorities, producing composite scores that reflect both what matters most to each stakeholder and how well each scenario performs in those areas. The full summary of every criterion, their indifference thresholds, scores, and contribution weight is presented in the Table 4.28.

The combined weighted results presented in the Table 4.29 reveal clear divergences in stakeholder preferences:

- Electrical Grid Operators and Road Operators show strong preference for the BEHDV + ERS scenario, mainly due to higher scores in land-use efficiency, grid load management, and long-term infrastructure cost-effectiveness.
- Shippers and Carriers also lean towards BEHDV + ERS, but mainly because of driver well-being and operational reliability, which rank high in their weight structures.
- Vehicle Manufacturers strongly favour the BEHDV-only scenario, as it outperforms across all their top criteria, particularly technological maturity and readiness.
- Freight Forwarders show a moderate preference for BEHDV-only, driven by higher operational flexibility - their highest-weighted criterion.

The integrated stakeholder-weighted results provide a consolidated view of how each scenario performs when both the quantitative performance of criteria and their relative importance are considered. While these findings offer a robust basis for comparison, they are inevitably influenced by the assumptions, input data, and methodological choices applied in this study. To assess the robustness of these results and identify which parameters most affect the final ranking of scenarios, a sensitivity analysis was conducted. The following section examines how variations in criteria weights and performance scores influence the overall scenario evaluation.

Table 4.28: Criteria with their calculated indifference thresholds, scores, and contribution weights.

Criteria	Weight	BEHDV (N1)	BEHDV + ERS (N2)	Indifference threshold	Score N1	Score N2	Contribution weight N1	Contribution weight N2
Cost Efficiency (Freight Rates)	0.461	0.03 EUR	0.028 EUR	0.0029 EUR	0.5	0.5	0.2305	0.2305
Reliability of Delivery Schedules	0.216	2.33	2.67	0.5	0.5	0.5	0.108	0.108
Sustainability / CO_2 Emissions Reduction	0.209	0 gCO_2/km	0 gCO_2/km	0 gCO_2/km	0.5	0.5	0.1045	0.1045
Well-being of Drivers	0.115	3.6	4.2	0.5	0	1	0	0.115
Total Cost of Ownership (TCO)	0.283	0.629 EUR/km	0.651 EUR/km	0.064 EUR/km	0.5	0.5	0.1415	0.1415
Access to Infrastructure	0.187	3.33	1	0.5	1	0	0.187	0
Operational Reliability	0.169	16-32%	10-20%	1.95%	0	1	0	0.169
Flexibility and Asset Utilization	0.153	2.8	1.6	0.5	1	0	0.153	0
Vehicle Payload and Weight	0.144	0.52	0.58	0.055	0	1	0	0.144
Driver Satisfaction	0.064	3.6	4.2	0.5	0	1	0	0.064
Profitability and Customer Demand	0.495	3	1.5	0.5	1	0	0.495	0
Infrastructure Readiness	0.22	5.67	3.33	0.5	1	0	0.22	0
Standardization and Interoperability	0.171	9	7-8	0.825	1	0	0.171	0
Long-Term Technology Risk	0.114	4	2.5	0.5	1	0	0.114	0
Grid Capacity Constraints	0.371	2.33	4	0.5	0	1	0	0.371
Policy Stability and Regulatory Support	0.306	4.5	2	0.5	1	0	0.306	0
Demand Density	0.18	2	5	0.5	0	1	0	0.18
Distributed Load Management	0.144	2	4	0.5	0	1	0	0.144
Investment and Maintenance Needs	0.471	0.072 EUR/km	0.048 EUR/km	0.006 EUR/km	0	1	0	0.471
Land Use Efficiency	0.385	50-100 m^2/km	7.5-10 m^2/km	4.19 m^2/km	0	1	0	0.385
Public Acceptance and Visual Impact	0.145	2.75	2.25	0.5	0.5	0.5	0.0725	0.0725
Operational Efficiency	0.376	3	1.33	0.5	1	0	0.376	0
Regulatory Compliance and Sustainability Goals	0.308	5	5	0.5	0.5	0.5	0.154	0.154
Cost Stability and Control (Energy Costs)	0.169	0	0.55	0.028	0	1	0	0.169
Competitive Advantage	0.147	4.25	4	0.5	0.5	0.5	0.0735	0.0735

Table 4.29: Composite weights per stakeholder for both scenarios.

Stakeholder	Composite weight of BEHDV scenario	Composite weight of BEHDV + ERS scenario	Preferred Scenario
Shippers	0.443	0.558	BEHDV + ERS
Carriers	0.482	0.519	BEHDV + ERS
Vehicle Manufacturers	1.000	0.000	BEHDV
Electrical Grid Operators	0.306	0.695	BEHDV + ERS
Road Operators	0.073	0.929	BEHDV + ERS
Freight Forwarders	0.604	0.397	BEHDV

4.9 Thematic Contribution of Weighted Performance

To complement the criterion-level analysis in previous section, the results of the normalised scores were aggregated into the three thematic categories defined in Section 4.3: Economic & Business Viability, Operational & Technical Performance, and Societal & Environmental Considerations. This aggregation provides a higher-level perspective on the composition of total weighted scores for each scenario, allowing the main thematic drivers of stakeholder preferences to be identified.

Table 4.30 presents the thematic contribution of weighted performance for all stakeholders combined. The Score columns for both scenarios represent the total contribution of all criteria within each theme after multiplication of stakeholder-specific weights by the normalised performance scores. The percentage for both scenarios columns indicate the share of each theme relative to the total weighted score for the respective scenario.

Table 4.30: Thematic contribution of weighted performance.

Theme	BEHDV (Score)	BEHDV (%)	BEHDV + ERS (Score)	BEHDV + ERS (%)
Economic & Business Viability	0.941	32.4%	1.266	40.9%
Operational & Technical Performance	1.329	45.7%	1.321	42.7%
Societal & Environmental Considerations	0.637	21.9%	0.510	16.5%

The results indicate that operational and technical performance criteria represent the largest share of the total weighted scores in both scenarios, accounting for approximately 46% in the BEHDV-only case and 43% in the BEHDV + ERS case. Economic and business viability criteria form the second-largest contribution; however, their relative importance increases markedly in the ERS scenario (from 32 % to 41 %). This increase reflects strong ERS performance in certain high-weighted economic criteria. Furthermore, societal and environmental considerations make up the smallest share of weighted scores in both scenarios, with a decline from 21.9 % in the BEHDV-only case to 16.5 % in the BEHDV + ERS case. This reduction is driven by modest ERS performance improvements in these criteria combined with generally lower stakeholder weightings assigned to them.

Overall, the thematic aggregation confirms that stakeholder preferences are predominantly shaped by economic and operational drivers, while societal and environmental considerations play a secondary role in scenario evaluation. The shift in the economic share towards the ERS pathway suggests that targeted improvements in economic performance could significantly influence the attractiveness of ERS adoption for certain stakeholder groups. These implications are explored further in the discussion chapter.

4.10 Sensitivity Analysis

For the criteria evaluated using quantitative indicators - particularly those with high influence on stakeholder preferences - sensitivity analysis reveals how variations in key assumptions could affect scenario outcomes and stakeholder alignment

Total Cost of Ownership

From the carrier perspective, the major drawback of ERS is the charges paid to use the infrastructure. If ERS infrastructure access fees were fully subsidised - such as through public funding - the resulting TCO could decrease by 14% to 0.557 EUR/km, making the ERS-enabled scenario 12% more cost-effective than the static-charging baseline. Given that TCO is a primary driver for both Carriers and Freight Forwarders, changes in this parameter have a higher effect on stakeholder preferences.

Vehicle Payload and Weight

The European Union (2022) currently allows a 2000 kg weight exemption for zero-emission trucks, partially compensating for heavier battery systems. The analysis used a 4441 kg weight difference between ERS- and non-ERS-equipped BEHDVs. If this exemption were increased to 4500 kg, it would eliminate the payload penalty for BEHDVs relying solely on static charging. As a result, the cost-efficiency advantage of ERS, derived from higher payload capacity, would be nullified. While important, this effect mainly influences the operational efficiency dimension and is less universally critical across stakeholders than the TCO.

Investment and Maintenance Needs

From the road operator perspective, the infrastructure cost calculation assumed a high level of utilisation for dynamic charging. If utilisation decreased by 50%, the annualised cost for ERS infrastructure would rise to 0.096 EUR/km, approximately 33% higher than static charging infrastructure. Since infrastructure cost is a decisive factor for Road Operators, Grid Operators, and public-sector actors, this assumption has high strategic importance.

Land Use Efficiency

The land-use calculation for the BEHDV-only scenario was based on MCS deployment assumptions (700-1500 kW). As MCS is not yet widely available in Europe, lower-power CCS systems may be more commonly used in the near term. Due to slower charging speed, a higher number and density of static charging installations would be required to maintain the same coverage and supply, potentially doubling land-use requirements. While land use is an important planning constraint - especially in urban and high-density corridors- its influence on overall stakeholder preference is less direct than cost-related criteria.

Overall, the sensitivity analysis highlights that cost-related parameters - particularly TCO for carriers and infrastructure investment requirements for road operators - carry the greatest potential to shift stakeholder preferences between scenarios. Operational and spatial factors, such as payload capacity and land use, can still influence scenario attractiveness but are less likely to drive fundamental changes in stakeholder alignment on their own. These findings reinforce the need to address cost-related barriers as a priority when designing policies and investment strategies for BEHDV and ERS deployment.

4.11 Summary of Findings

The results presented in this chapter offer a structured and transparent comparison between the BEHDV-only and BEHDV + ERS transition pathways, grounded in stakeholder-defined priorities. The analysis indicates a clear divergence in preferences. Stakeholders such as Electrical Grid Operators and Road Operators consistently favour the BEHDV + ERS pathway due to its potential advantages in infrastructure efficiency, grid load distribution, and long-term system optimisation. Shippers and Carriers also lean towards BEHDV + ERS, albeit more moderately, influenced mainly by perceived improvements in driver well-being and delivery reliability. In contrast, Vehicle Manufacturers strongly prefer the BEHDV-only pathway, driven by the importance they place on technological maturity, product readiness, and deployment feasibility. Freight Forwarders also show a moderate preference for BEHDV-only, primarily linked to operational flexibility, which carries significant weight in their evaluation.

Importantly, no single pathway emerges as the dominant solution across all stakeholders. This outcome highlights that the transition towards zero-emission heavy-duty road freight is inherently multi-dimensional, shaped by competing objectives, operational constraints, and sector-specific priorities. The findings suggest that rather than pursuing one exclusive pathway, a balanced and complementary approach - leveraging the strengths of both BEHDV-only and BEHDV + ERS - may better accommodate the diversity of stakeholder needs while maximising overall system benefits.

These results provide a structured foundation for examining the broader implications, trade-offs, and strategic considerations that arise when translating stakeholder-specific evaluations into actionable policy and industry decisions, which are explored in the following discussion.

5 Discussion

This chapter interprets the evaluation results presented in the previous section and reflects on the broader implications of the findings. The structure follows the MAMCA framework by linking stakeholder-specific criteria and indicator performance to the central research question: to what extent does the integration of ERS alongside BEHDVs enhance stakeholder value and operational feasibility in the transition to sustainable freight transport.

5.1 Key Findings

The analysis revealed distinct patterns in stakeholder preferences regarding the two transition pathways once performance indicators were normalised and weighted according to stakeholder-specific priorities.

1. **No universal preference across stakeholders**

The weighted results confirm that neither scenario is universally preferred. Composite scores in Table 4.29 show substantial variation: Road Operators allocate 93 % of their total weighted score to BEHDV + ERS, while Vehicle Manufacturers allocate 100% to BEHDV-only. Carriers (52% vs. 48%) and Shippers (56 % vs. 44%) show marginal differences, suggesting that their preferences could shift with relatively small changes in cost, performance, or policy.

2. **BEHDV-only favoured for technological maturity and operational flexibility**

Vehicle Manufacturers strongly prefer the BEHDV-only pathway, reflecting confidence in its market readiness, established supply chains, and the absence of dependence on large-scale new infrastructure. Freight Forwarders also lean towards BEHDV-only due to its higher operational flexibility, which they value most for meeting variable route demands. These preferences align with the thematic finding that BEHDV-only outperforms in high-weight operational and cost-critical criteria such as total cost of ownership, infrastructure readiness, and flexibility.

3. **BEHDV + ERS favoured for infrastructure efficiency and driver well-being**

Electrical Grid Operators and Road Operators show a strong preference for BEHDV + ERS, driven by advantages in grid load management, land-use efficiency, and long-term infrastructure cost-effectiveness. Shippers and Carriers also lean towards BEHDV + ERS, particularly due to perceived improvements in driver well-being and delivery reliability, criteria that, while not the most heavily weighted overall, can meaningfully influence adoption when cost differences are small.

4. **Operational performance as the leading contributor**

Thematic aggregation shows that Operational & Technical Performance criteria contribute the largest share of total weighted scores in both scenarios: 46% for BEHDV-only and 47 % for BEHDV + ERS. This dominance indicates that practical, functionality-related factors, such as access to infrastructure, delivery schedule reliability, and payload capacity, are decisive in shaping stakeholder assessments.

5. **Economic importance increases for ERS**

Economic and business viability criteria are the second-largest contributor overall, but their relative importance increases substantially in the ERS scenario, from 32% to 41%. This shift reflects ERS's strong performance in certain high-weighted economic criteria for infrastructure-focused stakeholders, particularly grid and road operators, and suggests that improving ERS cost competitiveness could strongly influence adoption decisions.

6. **Societal and environmental considerations remain secondary**

Societal and environmental considerations make up the smallest share in both scenarios, 22% for BEHDV-only and 17% for BEHDV + ERS. The reduction in the ERS case is driven by modest performance improvements in these criteria and generally low weighting assigned to them. While important for long-term policy goals, they are less decisive in short- to mid-term adoption choices.

7. **Cost-related factors have the highest potential to shift preferences**

Sensitivity analysis indicates that cost-related parameters, particularly total cost of ownership for Carriers and infrastructure investment needs for Road Operators, are the most influential levers for changing scenario preferences. Adjustments in these variables, such as targeted subsidies or revised infrastructure financing models, could reverse existing stakeholder alignments.

8. **Operational and spatial factors as secondary drivers**

Variations in payload allowances, journey time impacts, or land-use requirements affect scenario attractiveness but are less likely to cause fundamental shifts in stakeholder alignment compared to cost-driven parameters. Although, it is important to note that land availability is a physically limiting factor that might force stakeholders towards the ERS-enabled scenario due to absence of space for charging infrastructure.

9. **Complementary rather than exclusive adoption likely**

The divergence in stakeholder preferences, combined with the concentration of influence in a small set of high-weight criteria, suggests that a mixed deployment strategy is more viable than reliance on a single pathway. BEHDV-only provides immediate feasibility and aligns with current operational and technological readiness, while targeted ERS deployment on high-traffic corridors could deliver long-term infrastructure efficiency and grid optimisation benefits, especially for stakeholders managing physical transport networks.

These findings provide the analytical foundation for the subsequent discussion on trade-offs, alignment opportunities, and the broader implications for policy, infrastructure investment, and industry strategy.

5.2 Implementation Considerations

The thematic and stakeholder-specific analysis in previous sections shows that implementation pathways should be tailored to the groups most inclined to support them. Vehicle Manufacturers and Freight Forwarders are best positioned to accelerate BEHDV-only deployment given their alignment with technological readiness, established supply chains, and operational flexibility needs. Grid Operators and Road Operators can act as primary advocates for ERS due to the long-term infrastructure and grid efficiency benefits they prioritise. Shippers and Carriers, with their focus on driver well-being and delivery reliability, represent a potential swing group whose preferences could shift based on improvements in cost competitiveness and operational performance.

The evaluation results point to distinct adoption contexts for each pathway. BEHDV-only configurations are currently better suited for near-term deployment, particularly in wide-reaching and international logistics networks, due to higher infrastructure maturity, regulatory clarity, and operational flexibility. In contrast, ERS-integrated systems have the potential to deliver substantial system-level efficiency gains in the long term, but their viability will depend on strong policy direction, harmonised infrastructure planning, and targeted deployment on high-traffic corridors where utilisation levels can justify the investment.

Maximising the benefits of either pathway requires addressing current barriers and ensuring coordinated stakeholder action. For ERS, the most critical enablers include a clear policy mandate, alignment of freight corridor planning, standardisation of technology and operations, and secure funding mechanisms. Without these, economies of scale and interoperability - both essential to the business case - will be difficult to achieve.

Based on the analysis, several practical measures can guide further steps in the decarbonisation of heavy-duty road freight industry:

1. **Accelerate ERS research and large-scale trials**

Governments should take the lead in funding and coordinating ERS testing beyond pilot projects. Large-scale trials are essential to validate technical performance, cost projections, and operational feasibility under real-world conditions.

2. **Standardise infrastructure across borders**

A unified ERS standard within the European Union is necessary to ensure vehicle interoperability and enable cross-border freight flows. Regional or national ERS networks without harmonisation risk limiting scalability and economic viability.

3. **Targeted ERS deployment on high-traffic corridors**

Investments should prioritise routes with high freight density to maximise utilisation and cost-effectiveness, while static charging remains the backbone in lower-traffic areas.

4. **Implement targeted cost-reduction measures for ERS adoption**

For stakeholders sensitive to total cost of ownership and infrastructure investment, particularly Carriers and Road Operators, measures such as reduced ERS access fees, infrastructure co-financing, or utilisation-based charging models could significantly improve adoption potential and close the preference gap with BEHDV-only solutions.

5. **Design BEHDVs for future retrofitting**

Vehicle Manufacturers should incorporate provisions for adding ERS charging units post-purchase, allowing fleets to adapt as infrastructure availability expands.

6. **Maintain operational flexibility through battery sizing**.

For Carriers, full-battery BEHDVs remain more versatile in the current network context. Smaller batteries become viable only where ERS infrastructure provides reliable coverage.

7. **Develop hybrid deployment scenarios**.

Policymakers and infrastructure planners should explore mixed adoption strategies, with ERS concentrated on high-volume freight corridors and static charging in regional or last-mile contexts. Such hybrid models may better align with diverse stakeholder priorities while maximising network resilience.

8. **Enhance stakeholder collaboration**.

Shippers, Freight Forwarders, and Carriers should work together on network and operational planning to integrate BEHDVs effectively. Addressing current operational limitations compared to diesel trucks requires coordinated scheduling, route planning, and load management strategies.

9. **Engage underrepresented stakeholders early**

Future planning efforts should prioritise involving actors who were underrepresented in this research, such as Road Operators or Electrical Grip Operators, to capture operational and regulatory considerations critical to adoption.

10. **Assess the role of autonomous driving in decarbonisation strategies**.

Autonomous truck technology could significantly influence the economics and operational models of BEHDV and ERS adoption by improving vehicle utilisation rates, reducing labour costs, and enabling more predictable charging patterns. Policymakers, manufacturers, and infrastructure planners should explore how autonomous systems might be integrated into zero-emission freight corridors to maximise efficiency gains.

These considerations highlight that technology deployment decisions cannot be made in isolation from infrastructure planning, regulatory design, and cross-industry coordination. A phased, context-specific approach, aligning infrastructure investment with market readiness and targeting measures to the most influential stakeholders, will be essential to realise the potential of both BEHDV-only and ERS-enabled pathways.

5.3 Strengths and Limitations

While this study has certain methodological and empirical constraints, it also offers several notable strengths that enhance the relevance and robustness of the findings.

Strengths

- **Expertise of interview participants.** The interviewed experts were senior professionals from industry-leading companies, with extensive sector experience and decision-making responsibilities. Their insights ensured that the stakeholder criteria and evaluations were grounded in practical, high-level industry knowledge/
- **Integration of qualitative and quantitative evidence.** By combining literature data, expert interviews, and performance modelling, the evaluation captures both measurable technical aspects and stakeholder perceptions, increasing the depth of insights.
- **Application of MAMCA with stakeholder-specific weighting.** Using the Best-Worst Method to assign weights tailored to each stakeholder group ensures that the scenario evaluation reflects genuine differences in priorities rather than applying a uniform weighting scheme.
- **Structured performance measurement.** The normalisation and threshold-adjusted scoring process allowed indicators with different units and scales to be compared meaningfully while avoiding overemphasis on negligible differences.
- **Sensitivity analysis for robustness.** Testing the impact of key assumptions, especially for cost-related and infrastructure utilisation parameters, provided a clearer understanding of which factors most influence scenario preferences.

Limitations

- Methodological limitations:
    - **Stakeholder representation.** While the research included at least one expert from every stakeholder group apart from Road Operators, they were not always explicitly discussing the perspective of the stakeholder they most closely represent. This may affect the consistency and reliability of stakeholder-specific criteria identification and weighting.
    - **Stakeholder group generalisation.** Preferences within a stakeholder group may vary based on company size, strategy, or market segment, which could influence the weightings assigned to criteria.
    - **Modified BWM scale.** Using a 1-5 scale instead of the original 1-9 may have reduced granularity in preference expression.
    - **Government and other excluded stakeholders.** The perspectives of government, society, and drivers were not collected directly, despite their relevance to policy and public acceptance.
    - **Qualitative criteria indicators.** All criteria for Road Operators and Electrical Grid Operators were estimated qualitatively due to the absence of empirical ERS data, reducing the generalisability of the results for these groups.
- Empirical limitations:
    - **Small survey sample.** The survey to estimate Freight Forwarder criteria weights was completed by only two respondents, limiting the statistical robustness of results for this group.
    - **Reliance on modelled data.** Several indicators, particularly those related to ERS, relied on pilot project data, simulations, or expert assumptions rather than large-scale operational evidence, introducing uncertainty for long-term projections.
- Scenario design limitations:

- **Scenario independence assumption**. The evaluation assumes that BEHDV-only and ERS-supported scenarios develop independently, whereas in reality, their deployment is likely interdependent.
- **Path dependency of infrastructure rollout**. Early investments in static charging could either facilitate or constrain future ERS deployment, while ERS prioritisation could reduce investment in static charging networks. These dynamics are not captured in the current evaluation.

Despite these limitations, the combined qualitative-quantitative design, the structured application of MAMCA, and the involvement of highly experienced industry experts provide a robust, stakeholder-informed framework for comparing electrification strategies. The findings can serve as a valuable foundation for policymakers, infrastructure planners, and industry stakeholders seeking to navigate the complex transition to zero-emission heavy-duty road freight.

5.4 Recommendations

The findings of this study indicate several promising directions for future research that could strengthen the understanding and support of BEHDV and ERS adoption strategies. A key area requiring deeper investigation is the impact of ERS deployment on electrical grid operators. While this stakeholder group plays a critical role in the technical and economic viability of dynamic charging systems, it is frequently overlooked in both academic literature and policy discourse. Examining their operational, investment, and regulatory challenges in greater depth, particularly in relation to grid stability, capacity planning, and load management, would provide valuable insights into the broader system implications of ERS integration.

Furthermore, the methods used to determine stakeholder criteria weightings could be refined. Achieving higher accuracy would benefit from engaging directly with representatives from each stakeholder group and employing more granular techniques such as pair-wise comparison. Although this approach increases the complexity of survey participation, its capacity to capture nuanced differences in preference hierarchies could substantially improve the robustness of the results.

Future work could also focus on case studies dedicated to specific stakeholder sub-groups, recognising the diversity of perspectives within each category. For example, SME carriers may differ significantly from large fleet operators in their priorities and constraints, potentially leading to divergent adoption pathways. A more targeted approach would allow researchers to identify these variations and assess how they influence broader network-level outcomes.

Finally, expanding the scenario framework to include intermediate configurations between the BEHDV-only and BEHDV + ERS pathways would offer valuable insights into the optimal degree of dynamic charging integration. Modelling scenarios with partial ERS coverage or hybrid charging networks could reveal tipping points where system-level benefits are maximised, thereby informing more balanced and cost-effective infrastructure planning.

6 Conclusion

This thesis set out to evaluate the extent to which integrating ERS alongside BEHDVs can enhance stakeholder value and operational feasibility in the decarbonisation of long-haul road freight. The research was motivated by a clear scientific and practical gap: while the academic literature has extensively assessed BEHDVs and, to a lesser extent, ERS in isolation, very few studies have compared these pathways from a multi-stakeholder perspective, combining both quantitative performance evaluation and qualitative insight. Moreover, stakeholder-specific adoption criteria, priorities, and trade-offs, particularly for underrepresented actors such as electrical grid operators and road infrastructure managers, have not been systematically integrated into comparative scenario analysis.

By applying the MAMCA framework in combination with the BWM, this study provides a very comprehensive, stakeholder-driven assessments of BEHDV and ERS adoption pathway. It captures the perspectives of six key stakeholder groups, addressing both the technical feasibility and the strategic alignment of each electrification pathway. The approach advances existing knowledge by explicitly linking stakeholder weightings to scenario performance outcomes, producing a nuanced, evidence-based understanding of where each technology is likely to deliver the greatest value.

RQ1: Who are the decision maker stakeholders that are involved in the adoption of BEHDVs and ERS?

Six key stakeholder groups were confirmed to have decisive influence over BEHDV and ERS adoption: carriers, shippers, vehicle manufacturers, freight forwarders, electrical grid operators, and road infrastructure managers. Each brings a distinct operational and strategic lens to the adoption decision, making their simultaneous consideration essential for designing effective and inclusive policies..

RQ2: What evaluation criteria do key these stakeholders use to assess the adoption of BEHDVs with and without ERS?

The research identified a diverse set of evaluation criteria for each stakeholder group, spanning economic, operational, societal, and environmental themes. Across stakeholders, economic and business viability criteria consistently emerged as the highest priority, followed by operational and technical performance, with societal and environmental considerations weighted lowest. This pattern highlights that technology adoption in the freight sector is still primarily driven by cost structures and operational feasibility rather than climate impact or public acceptance.

RQ3: What is the relative importance of the identified evaluation criteria for each stakeholder in the context of BEHDV adoption with and without ERS?

The application of the BWM revealed clear differences in criteria weightings across stakeholder groups. For example, total cost of ownership was the dominant consideration for carriers, while grid load management and land-use efficiency were key for grid and road operators. These weightings directly influenced the performance evaluation and the resulting stakeholder-specific scenario preferences.

RQ4: How do the adoption options of BEHDVs with and without ERS perform when evaluated against stakeholder-specific criteria and priorities?

The combined weight and performance analysis showed that BEHDV-only configurations are currently more attractive for carriers, freight forwarders, and vehicle manufacturers due to advantages in operational flexibility, infrastructure readiness, and technological maturity. Grid operators and road managers strongly preferred ERS for its potential to optimise grid loads, improve land-use efficiency, and reduce long-term infrastructure costs. Shippers and carriers displayed more balanced preferences, with ERS gaining an advantage in driver well-being and delivery reliability, though cost competitiveness remains decisive.

The findings make clear that there is no single universally superior pathway. BEHDV-only solutions are better suited for rapid near-term deployment thanks to their existing infrastructure maturity and regulatory clarity, while ERS holds strategic potential in high-density freight corridors where its benefits can be maximised and its drawbacks mitigated. The results show that these two approaches should be seen as complementary rather than mutually exclusive. A phased adoption strategy, scaling up BEHDV deployment via static charging while preparing the technical, institutional, and regulatory foundations for ERS, offers the best balance between short-term feasibility and long-term system efficiency

This work makes a novel contribution by closing a significant research gap: the lack of integrated, stakeholder-driven comparative assessment of BEHDV and ERS pathways. By explicitly connecting stakeholder-specific weightings to performance outcomes, it delivers actionable insights for policymakers, planners, and industry leaders. The research not only deepens academic understanding of freight-sector electrification trade-offs but also provides a decision-support framework adaptable to future technological and policy contexts. Its stakeholder-centric design ensures that the results are grounded in the realities of the freight ecosystem, making them directly relevant for shaping practical decarbonisation strategies

In conclusion, achieving climate neutrality in long-haul road freight will require more than a single technological solution. The most resilient and impactful pathway will combine the immediate scalability of BEHDV-only systems with the long-term systemic benefits of targeted ERS deployment, aligning infrastructure investment, regulatory design, and stakeholder priorities into a coherent transition strategy. Ultimately, the shift to zero-emission long-haul freight will not be driven by technology alone, but by aligning technical capabilities with the priorities of those who design, operate, and regulate the system. By bridging the gap between stakeholder realities and infrastructure strategy, this research offers a clear roadmap for transforming electrification from a technological possibility into an operational and economic inevitability.

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Appendix A: Edited transcripts of the interviews with industry experts

A.1 Stakeholder Expert 1

Date: 11 April 2025

Time: 11:20

Carriers

Benediktas Opeikis: From the perspective of carriers, what key criteria influence the adoption of BEHDVs?

Stakeholder Expert 1: The main issue is infrastructure for both static or dynamic charging - its existence, coverage, and availability. In the case of ERS, If you electrify an entire corridor, such as the Brenner, and make it available reliably, that already solves many problems. If the infrastructure works and is always available, like with electrified train lines, then carriers can plan around it.

Benediktas Opeikis: What about concerns around asset flexibility? For example, if a carrier buys an ERS-compatible truck for a specific route, what happens if that contract ends or the customer shuts down?

Stakeholder Expert 1: I don't think that's a big issue. Let's say you're operating on a key corridor like Brenner. Even if the customer goes away, that corridor still connects important logistics points. You have flexibility along that route - you can go out at Munich, Verona, Bologna. If the highway is fully electrified, it gives you options. Right now, with electric trucks, the flexibility is already quite limited. If you buy a truck under a five-year financing agreement and lose your customer, you still need another with the same requirements. So I'd say the ERS doesn't make the situation worse; it might actually improve flexibility.

Benediktas Opeikis: How do current battery ranges align with operational constraints like driver working hours?

Stakeholder Expert 1: For example, with a 620 kWh battery, you can already align the range of the vehicle with the driver's legal driving hours. You need to stop anyway, so if you fast-charge during breaks, it doesn't disrupt the logistics chain. You don't necessarily need bigger batteries. The problem is that people expect to make this switch without changing anything in their operations, and that's just not realistic.

Benediktas Opeikis: So logistics models need to adapt?

Stakeholder Expert 1: Absolutely. If you want to bring electric trucks into the supply chain, you need to change the model. Right now, we're used to the flexibility of a diesel truck with 2,000 km of range. But electric vehicles are different. You need to plan for range, charging, trailer swapping, even reallocation along a corridor. We've tested this model at Gruber Logistics, and while it's promising, it needs more evaluation. Also, we have to update our IT tools to manage all this.

Benediktas Opeikis: Do current charging networks support that level of operational integration?

Stakeholder Expert 1: Not yet. There's no booking system. The chargers often aren't designed for trucks - they were made for cars. You go to a 350 kW charger, but when you plug in, you might get 100 kW. That could be due to the grid, other users charging, or weather conditions. You can't rely on it. And the lack of consistency creates problems in logistics. If you're late, you miss delivery slots, get penalties - it's a mess.

Benediktas Opeikis: And the cost?

Stakeholder Expert 1: It's extremely high. Electric trucks are expensive, and the use cases are still rare. We have around ten electric trucks, and we use them domestically. Internationally, there aren't theoretical constraints, but practically, there's no infrastructure. Also, regulation on weight limits varies by country. One country might allow 44 tons for electric trucks, another might stick to 40. So you constantly have to check if your load is compliant.

Benediktas Opeikis: Any operational benefits?

Stakeholder Expert 1: There are soft benefits - reduced noise, better driver comfort, wellness. These are valuable but not enough to offset the hard limitations on logistics planning. The vehicles themselves are very expensive. You're handling equipment that's sometimes worth more than the cargo. That has implications for risk and security, especially if battery swapping becomes an option. You'd have a location with several million euros worth of batteries - it's like a bank vault.

Benediktas Opeikis: What about the idea that battery technology alone will solve these problems?

Stakeholder Expert 1: No, I don't buy into that narrative. The energy density will improve, yes, but that won't eliminate the need to revise logistics models. It's a myth that you can plug electric trucks into the current model and everything will be fine. We're already seeing that with our own pilots. You need to rethink operations from the ground up.

Vehicle Manufacturers

Benediktas Opeikis: What do OEMs prioritize when considering the production of BEHDVs or ERS-compatible models?

Stakeholder Expert 1: A major barrier is the absence of standardized infrastructure. For solutions like battery swapping or dynamic charging to work, full interoperability is essential. However, OEMs resist standardization efforts - particularly those imposed through legislation - because they want to maintain flexibility in their product strategies. This resistance limits scalable adoption.

Additionally, the technology for dynamic charging, such as pantographs, still lacks widespread demonstration of feasibility and cost-effectiveness. Manufacturers are unlikely to invest heavily without a clear business case and regulatory certainty.

Grid Operators

Benediktas Opeikis: How do infrastructure and grid operators view the transition to BEHDVs and ERS?

Stakeholder Expert 1: The grid is often overlooked in policymaking, despite being one of the biggest limitations. In several cases, we encountered situations where the grid couldn't support fast-charging installations, even when grants were available for the chargers themselves. Often, 70-80% of total project costs come from grid upgrades, which are not eligible for reimbursement under current funding schemes. This results in companies not applying for grants despite the need for chargers.

ERS, on the other hand, could mitigate peak load problems by distributing power demand over time and space. Its availability, if ensured, would be one of its biggest advantages compared to static chargers.

Shippers

Benediktas Opeikis: What are the primary criteria for shippers in the context of BEHDVs and ERS?

Stakeholder Expert 1: It varies widely. Small and medium-sized enterprises (SMEs) are generally not prioritizing EV adoption, while large companies may show interest if sustainability policies are embedded in their company goals procurement practices. However, such initiatives are rarely driven by the logistics departments themselves. In most cases, EVs are only adopted when a clear partnership is formed and when the shipper is willing to co-invest or adjust logistics to accommodate the change.

Road Operators

Benediktas Opeikis: And how do road operators fit into this transition?

Stakeholder Expert 1: Road operators are a critical but often silent stakeholder in this discussion. Successful deployment of ERS requires a coordinated top-down approach at the European level. Otherwise, fragmented decision-making between jurisdictions can block development. Without a unified framework, road operators will struggle to support dynamic infrastructure due to visual, regulatory, and technical hesitations.

Technological Alternatives and Final Remarks

Benediktas Opeikis: Are there technological alternatives to dynamic charging that could facilitate BEHDV adoption without requiring such systemic change?

Stakeholder Expert 1: Battery swapping is a potential alternative that would simplify operations, but it faces opposition from OEMs due to standardization constraints. Additionally, it raises security concerns - batteries are expensive and easily removable in swapping models, which creates theft risk and complicates liability.

In terms of battery development, higher energy density will help but will not remove the need for systemic changes in logistics models. The idea of seamlessly replacing a diesel truck with an electric one, without adjusting operations, is unrealistic. We have piloted electric truck use, and adapting routing and scheduling was essential. Technology will improve, but so must the operational frameworks.

Benediktas Opeikis: Thank you very much for your time and insights. This has been extremely valuable.

Stakeholder Expert 1: You're welcome. Looking forward to seeing the outcomes of your research.

A.2 Stakeholder Expert 2

Date: 22 January 2025

Time: 08:34

Benediktas Opeikis: In my research, I’ve identified four key stakeholders: shippers, carriers, freight forwarders, and vehicle manufacturers. Are you comfortable discussing these groups, or would you like to suggest other relevant stakeholders?

Stakeholder Expert 2: Those are key stakeholders, but you’re missing an important one: the infrastructure operator, or what we call the Charge Point Operator (CPO). Without infrastructure, neither BEVs nor ERS can function effectively. This group includes grid operators and entities managing the electrical systems. For simplicity, we can refer to all of them as CPOs.

Benediktas Opeikis: Good point. The infrastructure is a critical enabler. Shall we begin with manufacturers, given your expertise?

Stakeholder Expert 2: Sure, let's start there.

Vehicle Manufacturers

Benediktas Opeikis: What criteria do manufacturers prioritize when producing BEVs, particularly heavy-duty vehicles? How do these criteria change when considering ERS compatibility?

Stakeholder Expert 2: Manufacturers prioritize profitability above all. For a viable business case, we need customers willing to invest in the vehicles. This depends on the electricity price and the overall return on investment (ROI) for the customer. Additionally, we require a minimum number of vehicles to justify production and achieve economies of scale.

ERS introduces new considerations. For example, manufacturers must evaluate the long-term viability of the technology. Investing heavily in ERS-compatible vehicles is risky if the infrastructure isn't widely adopted or if another disruptive technology takes over within a few years. Ideally, we look for a horizon of at least 10 years to ensure sustainability.

Benediktas Opeikis: How do you address the risk of alternative technologies replacing ERS in the future?

Stakeholder Expert 2: This is a major concern. While we can't guarantee that ERS will dominate the market indefinitely, we rely on qualified estimations based on market trends, government policies, and the current technological landscape. We evaluate whether the technology aligns with long-term legislative and industry goals. Still, all investments carry some risk, so we reduce uncertainty by conducting detailed evaluations.

Benediktas Opeikis: How do you measure or estimate the long-term viability of such technologies?

Stakeholder Expert 2: Business case evaluations are crucial. In Germany alone, we've conducted 20-30 studies assessing ERS's potential. A critical factor is the infrastructure's scale and location. For instance, a dense, high-traffic corridor of 100 kilometers between two major cities is a promising starting point.

Benediktas Opeikis: Does infrastructure availability directly influence manufacturers?

Stakeholder Expert 2: Absolutely. While the ERS technology itself is proven and operational, as demonstrated in Germany, we're currently at a standstill because no additional roads are being developed. Without infrastructure expansion, manufacturers like Scania can't justify further investment.

Benediktas Opeikis: Are standards and compatibility an issue for manufacturers?

Stakeholder Expert 2: Yes, standardization is essential. While static charging standards like CCS and MCS are well-developed, dynamic charging standards at various stages of development, for example overhead charging standards are developed while other types are still working on the standardisation. ERS standards are still evolving. For manufacturers, adopting a solution requires confidence that it will align with future standards to avoid stranded investments. Collaboration across the industry is critical here.

Carriers

Benediktas Opeikis: Moving on to carriers: What criteria might they prioritize when adopting BEHDVs, and how would ERS change these priorities?

Stakeholder Expert 2: For carriers, reliability and cost-efficiency are paramount. They need to deliver goods on time and at competitive costs. BEHDVs' battery weight reduces payload capacity, which is a concern for many operators. However, ERS alleviates this issue by allowing smaller batteries, thereby increasing payloads and reducing costs.

Another advantage of ERS is the elimination of charging delays. With ERS, trucks can charge while driving, enabling carriers to rest at convenient locations instead of queuing at charging stations. This flexibility improves operational efficiency by reducing the time spent at rest stops that are dictated by charging needs.

Benediktas Opeikis: How would you measure reliability in this context?

Stakeholder Expert 2: One key metric is uptime - the percentage of time the ERS infrastructure is operational. Maintenance and repairs should only affect small sections at a time, allowing trucks to switch to battery mode temporarily. This redundancy ensures minimal disruption.

Benediktas Opeikis: What about driver perspectives? Do they play a role in carrier decision-making?

Stakeholder Expert 2: Yes, driver satisfaction is an important factor. BEHDVs and ERS-equipped vehicles offer a quieter, more comfortable driving experience, which helps attract and retain drivers. Given the ongoing driver shortage, this is a significant advantage.

Shippers

Benediktas Opeikis: What about shippers? What are their main considerations for adopting BEVs, and how might ERS play a role?

Stakeholder Expert 2: Shippers fall into two broad categories. Some prioritize sustainability and demand zero-emission transport, which BEHDVs and ERS can both achieve. Others focus solely on cost. For them, the decision will hinge on whether BEHDVs or ERS offer the lowest total cost of ownership.

Road and Grid Operators

Benediktas Opeikis: Let's discuss infrastructure operators. What challenges and opportunities do they face?

Stakeholder Expert 2: Infrastructure operators need a strong business case, as the upfront investment is substantial. Public-private partnerships are likely necessary, with governments playing a leading role in funding. One advantage of ERS is that it distributes the electrical load across a road network, avoiding the need for large, concentrated grid connections like those required for static charging stations.

Additionally, ERS reduces the space needed for static chargers, which is a growing concern in densely populated areas. The main challenge is political will and securing the initial funding to build showcase projects that can demonstrate the system's potential.

Benediktas Opeikis: How do grid operators manage the challenges of electricity demand?

Stakeholder Expert 2: ERS spreads the electricity demand along the road network, making it easier to manage compared to concentrated demand at static charging hubs. For example, instead of needing 100 MW at one location, you can distribute 2 MW increments along the road, which is far more practical.

Common Themes and Closing Thoughts

Benediktas Opeikis: Across all stakeholders, the business case seems to be a recurring theme. Are there any other unifying factors or collaborative opportunities?

Stakeholder Expert 2: Collaboration is key, especially in addressing shared challenges like grid capacity and infrastructure development. For instance, ERS can solve future bottlenecks in static charging infrastructure. However, stakeholders need a long-term perspective - something that is often difficult for politicians due to election cycles.

Overall, BEHDVs and ERS are complementary technologies. The choice depends on the specific use case, but both contribute to the broader goal of decarbonizing transport. The challenge lies in aligning incentives and ensuring that infrastructure and vehicle technologies evolve together.

Benediktas Opeikis: Thank you for your insights. This has been incredibly valuable for my research. I'll follow up with a summary and survey for your feedback.

A.3 Stakeholder Expert 3

Date: February 7, 2025

Time: 13:19

Carriers

Benediktas Opeikis: What criteria do carriers prioritize when deciding to adopt BEHDVs?

Stakeholder Expert 3: Carriers focus on one thing - profitability. If a truck costs more to purchase, it needs to either cost less to operate or generate more revenue to justify the investment. That means TCO and return on investment (ROI) are key. Carriers will compare operational costs like fuel, maintenance, and downtime to determine whether an electric truck makes financial sense.

Benediktas Opeikis: Would these criteria change if ERS were introduced?

Stakeholder Expert 3: Not significantly. The core principle remains the same - profitability. If ERS enables lower operational costs, improves uptime, or increases revenue-generating potential, carriers will consider it. However, they won't invest in ERS-compatible vehicles unless they see a reliable business case and sufficient infrastructure coverage.

Freight Forwarders

Benediktas Opeikis: How do freight forwarders approach BEHDV adoption?

Stakeholder Expert 3: It depends on their size and strategy. Some freight forwarders take a "check-the-box" approach, running a single electric truck to meet sustainability goals. Others leverage government subsidies to fund pilot projects. A few, like sennder, see strategic potential in electric trucking and are working to scale adoption because we believe it will be more cost-effective than diesel in the near future.

Benediktas Opeikis: What are the key benefits for freight forwarders adopting BEHDVs?

Stakeholder Expert 3: The most overlooked advantage is control over energy costs. Unlike diesel, which fluctuates in price and is entirely dependent on external suppliers, electricity costs can be managed. A freight forwarder with its own renewable energy or battery storage can significantly reduce costs and stabilize pricing. If done correctly, electricity can be cheaper than diesel, reducing long-term operational expenses. Another major advantage is accessibility to emission free zones.

Benediktas Opeikis: What are the challenges?

Stakeholder Expert 3: The biggest challenge is range. Most BEHDVs today operate between 300-500 km per charge. Once battery ranges reach 600 km+, range anxiety will disappear. Until then, planning remains difficult, especially for long-haul operations. While ERS could theoretically solve this, static charging infrastructure is already growing rapidly. It's unclear if dynamic charging will offer significant advantages.

Vehicle Manufacturers

Benediktas Opeikis: What factors drive manufacturers in producing BEHDVs?

Stakeholder Expert 3: Manufacturers prioritize maintaining and expanding their customer base. They know diesel will be replaced by electric, so they're scaling up BEV production. However, they face two major pressures: customer demand and legislative requirements. EU regulations penalize manufacturers that don't reduce fleet emissions, pushing them to accelerate electrification.

Benediktas Opeikis: How does ERS factor into their considerations?

Stakeholder Expert 3: Manufacturers won't build ERS-compatible trucks unless there's a critical mass of infrastructure. Currently, Europe has around 250,000 EV charging points, nothing to compare with roads that offer dynamic charging capabilities. Until there's meaningful ERS coverage, manufacturers won't prioritize compatibility.

Grid Operators

Benediktas Opeikis: What challenges do grid operators face in supporting BEHDV adoption?

Stakeholder Expert 3: The grid has two primary challenges: transmission and distribution. The high-voltage transmission grid moves electricity long distances, while the distribution grid connects directly to users. The transmission grid must integrate increasing renewable energy sources, while the distribution grid faces bottlenecks in connecting new charging points. Upgrading distribution grids takes time - sometimes up to three years - creating a major bottleneck.

Shippers

Benediktas Opeikis: What are the key priorities for shippers in adopting BEHDVs?

Stakeholder Expert 3: Cost and emissions. Every shipper operates on a budget, so cost competitiveness is non-negotiable. Some shippers have strict CO_2 reduction targets, making low-emission transport a priority. Others prioritize cost over sustainability, but if green transport offers cost savings, they'll adopt it.

Benediktas Opeikis: Could shippers play a role in BEHDV adoption beyond procurement?

Stakeholder Expert 3: Absolutely. Many shippers have large grid connections and could provide charging infrastructure for carriers. Some already own renewable energy assets, which could make electrification even more cost-effective.

Common Trends & Closing Thoughts

Benediktas Opeikis: Are there any common trends that could facilitate faster BEHDV and ERS adoption?

Stakeholder Expert 3: Three key trends stand out:

1. **Zero-Emission Tolls:** Governments could reduce or eliminate toll fees for zero-emission vehicles, improving their cost competitiveness.

2. **Grid Connection Expansion:** Increasing the number of charging points and improving grid accessibility will be crucial.
3. **Technology Learning Curve:** Adoption takes time. The faster stakeholders learn how to integrate BEHDVs efficiently, the quicker adoption will scale.

Benediktas Opeikis: Thank you for your insights. This has been incredibly valuable for my research.

A.4 Stakeholder Expert 4

Date: 16 April 2025

Time: 14:08

Vehicle Manufacturers

Benediktas Opeikis: Let's begin with manufacturers. What is the industry's stance toward ERS and electrification?

Stakeholder Expert 4: Electric roads pose a challenge for OEMs. They shift investment from vehicles to infrastructure, which affects OEMs' business models. For example, smaller batteries mean lower truck prices and potentially reduced revenues. That's not particularly attractive to them.

In terms of product development, most heavy-duty electric trucks today are conversions of diesel platforms. They are not built from the ground up for electrification, unlike the Tesla Semi, which has shown superior performance because it was designed as an electric truck from day one. European OEMs carry legacy constraints that make innovation slower.

Moreover, there is a lobbying challenge. OEMs have been pushing for fast-charging infrastructure (MW charging), and they hesitate to publicly advocate for ERS because it sends mixed messages to policymakers. This limits their willingness to promote dynamic charging solutions.

Benediktas Opeikis: Would ERS-compatible trucks be less complex or cheaper?

Stakeholder Expert 4: Yes, definitely. If ERS enables smaller batteries, the trucks can be lighter, cheaper, and allow higher payloads. But until the infrastructure exists, OEMs are unlikely to prioritize ERS compatibility.

Carriers

Benediktas Opeikis: What do carriers prioritize in this transition?

Stakeholder Expert 4: Carriers care about operational efficiency. They don't want trucks sitting idle just to charge. Ideally, charging happens during loading or unloading. Electreon's wireless systems start charging as soon as a truck is parked at a dock—no cables, no human interaction. That saves time.

However, if a carrier hasn't yet adopted electric trucks, the investment requirements can be daunting. Many don't even have sufficient grid connection at their depot. Upgrading can be prohibitively expensive, and banks are often reluctant to finance such upgrades.

Also, carriers prefer to charge on-site for security and cost reasons. Public infrastructure is riskier and often more expensive. Dynamic charging, while potentially more costly per kWh, enables charging on the move and avoids idle time. That improves utilization.

Benediktas Opeikis: Does dynamic charging change utilization?

Stakeholder Expert 4: Yes, significantly. With static charging, trucks must stop and occupy space. That's unproductive time. With ERS, energy is transferred while driving, which means fewer breaks, better asset utilization, and more predictable operations. Plus, it simplifies logistics planning, particularly if booking systems for chargers are unreliable or unavailable.

Grid Operators

Benediktas Opeikis: How does ERS compare to static charging from a grid operator's perspective?

Stakeholder Expert 4: ERS distributes energy consumption over time and space, flattening the load. With static charging - especially MW charging - you get large, unpredictable peaks at specific times, like morning, noon, or evening. That stresses the grid and increases costs.

Moreover, only a few MW chargers have been deployed in Europe. It's a myth that this infrastructure is widely available. The scale needed for large-scale electrification is enormous. A study by VINCI in France showed that to electrify just 25% of heavy-duty trucks, 7,000 new truck parking spots would be required. That's nearly a 20% increase, and truck charging also requires more space than diesel fuelling.

If we aim for 50% or more electrification, these issues multiply. ERS sidesteps many of these constraints.

Shippers

Benediktas Opeikis: From a shipper's point of view, what matters most in this transition?

Stakeholder Expert 4: Almost all companies using electric trucks today are doing so for environmental reasons. Cost is important, but most shippers do not care whether a truck is charged statically or dynamically. They care about CO2 footprint and total cost.

That said, battery manufacturing has a huge CO2 footprint. If ERS allows for smaller batteries, it can substantially reduce lifecycle emissions. This matters more as shippers increasingly focus on scope 3 emissions and environmental reporting.

Road Operators

Benediktas Opeikis: What are the implications for road operators?

Stakeholder Expert 4: Static charging infrastructure requires more land, especially for large-format MW chargers. Parking lots and rest areas are already overcrowded. If fast chargers are installed, the layout has to be redesigned to fit trucks, which further reduces capacity.

ERS, by contrast, doesn't need dedicated stops. Charging is done while driving. It's not only more efficient but also less invasive in terms of land use. From a road operator's view, integrating ERS with existing infrastructure avoids the need for massive reconfiguration of rest areas and parking capacity.

Closing reflections

Benediktas Opeikis: What are the biggest opportunities and challenges moving forward?

Stakeholder Expert 4: The biggest challenge is timing. OEMs are under pressure to get electric trucks to market. There's limited capacity to consider long-term systems like ERS. But this creates a risk of missing the bigger picture.

European OEMs are already lagging in bus electrification compared to Chinese manufacturers like Yutong. The same could happen in trucks. We must balance short-term needs with long-term system benefits.

ERS is a radical solution, but one with strong long-term promise. The difficulty is aligning stakeholders' incentives - manufacturers, carriers, road and grid operators, and policymakers - to coordinate action. The politics of energy independence, raw material sourcing, and grid stability will increasingly drive interest in ERS as a strategic infrastructure investment.

Benediktas Opeikis: Thank you very much for your time and insight.

A.5 Stakeholder Expert 5

Date: February 17, 2025

Time: 12:19

Vehicle Manufacturers

Benediktas Opeikis: What criteria do vehicle manufacturers prioritize when producing Battery Electric Heavy Duty Vehicles (BEHDVs), and how does ERS impact these priorities?

Stakeholder Expert 5: The key selling point for dynamic charging is reducing the cost of electrifying freight transport. If we can reduce battery size through ERS, the total cost of ownership (TCO) improves, speeding up adoption and reducing resource dependency. However, there are investment concerns—who will fund the infrastructure?

Manufacturers like Renault and Volvo Trucks recognize that electrification is happening and are preparing accordingly. While ERS is not a prerequisite, standardization is a critical issue. The technology has been tested and works, but investment remains uncertain. Inductive charging is especially challenging for heavy trucks due to its slower charging rate.

Another challenge is interoperability across European markets. Roaming electricity agreements across countries are complex, and ensuring seamless energy supply for trucks moving across borders will be critical.

Carriers

Benediktas Opeikis: What criteria do carriers consider when deciding to adopt BEHDVs, and how does ERS change these considerations?

Stakeholder Expert 5: Carriers ask two fundamental questions: *What is the price?* and *How do I charge?* The cost of BEHDVs is currently 2-3 times that of a diesel truck, making reassurance on return on investment essential.

Operational range is a major concern. With ERS, charging could happen during driving, reducing reliance on scheduled stops. This simplifies break planning and increases flexibility, making drivers happier. However, carriers are often sceptical at first. While they may be hesitant when discussing electric trucks, 100% of those who have used them do not want to switch back to diesel.

Additionally, access to zero-emission and low-noise zones is a growing advantage, as diesel trucks are increasingly restricted from entering certain areas.

Freight Forwarders

Benediktas Opeikis: What criteria are relevant for freight forwarders when adopting BEHDVs and ERS?

Stakeholder Expert 5: Freight forwarders aim to optimize truck performance, often working closely with carriers. Cost reduction is a major driver. Performance optimization depends on agreements with carriers, but factors such as driver behaviour (which can impact energy consumption by up to 20%) and efficient charging management play a role.

A key advantage is price stability. Diesel prices fluctuate, but electricity pricing can be managed through procurement strategies, reducing volatility. Another major benefit is that BEHDVs eliminate the need to account for charging times in operational planning—this efficiency is valuable for carriers and freight forwarders alike.

Freight forwarders also recognize that offering electric freight services gives them a competitive advantage. Companies that adopt early will be better positioned as regulations tighten.

Shippers

Benediktas Opeikis: What are the key considerations for shippers in adopting BEHDVs?

Stakeholder Expert 5: Shippers primarily focus on cost and emissions. Large B2C companies with strict CO_2 targets are the primary early adopters. These companies need to reduce their carbon footprints, and transport emissions represent an easy target.

Smaller companies are less proactive. They will likely transition only when legislation makes diesel trucking more expensive through carbon taxes or emission-based fees. In the long run, cost competitiveness will drive adoption—once electric transport becomes cheaper than diesel, businesses will shift naturally.

Road & Grid Operators

Benediktas Opeikis: What challenges do infrastructure operators face in supporting BEHDV and ERS adoption?

Stakeholder Expert 5: The major challenge is the investment required for ERS infrastructure. It's a significantly larger financial commitment than building static charging stations. Grid operators face a related issue: the high-power demands of electric trucking. Static chargers already strain local grids, and ERS would require substantial upgrades.

Another challenge is ensuring compatibility between ERS infrastructure and existing electricity supply frameworks across multiple countries. Roaming agreements and standardized payment systems for electricity use will need to be established. Additionally, road operators must determine how to integrate ERS infrastructure with existing road networks while minimizing disruptions and maintenance costs.

The lack of standardization in dynamic charging also complicates widespread deployment. Policy and financial incentives from governments will be necessary to overcome these barriers.

Challenges & Opportunities

Benediktas Opeikis: What key trends or policies could facilitate faster BEHDV and ERS adoption?

Stakeholder Expert 5: Governments need to commit to long-term policies that support electrification. This includes:

- Maintaining subsidies to offset high initial costs.
- Speeding up permitting and application processes for infrastructure.
- Implementing CO_2 reduction targets and penalties to drive adoption.

The question is whether governments will stick to their commitments. Without clear policies, businesses hesitate to invest.

Another emerging issue is road operator involvement. Roads must be adapted to support ERS infrastructure, creating additional complexity. Ensuring that road and grid operators align with electrification goals will be key to success.

Closing Thoughts

Benediktas Opeikis: Across all stakeholders, cost and infrastructure seem to be recurring themes. Any final insights?

Stakeholder Expert 5: The transition to electric trucking is inevitable, but it requires coordinated action from multiple stakeholders. The technology is ready, but investment remains the biggest challenge. Freight forwarders, carriers, and manufacturers must work together to optimize operations, while governments must provide stable policy frameworks to encourage infrastructure investment. With the right approach, electrification will scale rapidly.

Benediktas Opeikis: Thank you for your insights. This has been incredibly valuable for my research.

A.6 Stakeholder Expert 6

Date: 21 January 2025

Time: 13:07

Carriers

Benediktas Opeikis: What specific criteria do you think carriers prioritize when deciding to adopt BEHDVs?

Stakeholder Expert 6: Carriers focus primarily on cost efficiency, operational reliability, and flexibility. However, they also take into account factors such as payment terms from manufacturers, network density, and the availability of station-based infrastructure.

Another important factor is vehicle lifespan, as carriers want to ensure that their investment will last. They also consider demand from shippers and potential legal requirements pushing for zero-emission transport. Reassurance on return on investment (TCO) is key.

Interestingly, many carriers are willing to pay a premium - around 15,000 EUR - to ensure that their heavy-duty vehicles are compatible with ERS. For light commercial vehicles (LCVs), this figure is lower.

Additionally, electricity prices and the ease of operating the system are crucial. Increased vehicle utilization is another benefit ERS can bring, as it reduces time spent at charging stations. However, most mid-sized carriers do not have specific emission targets and are currently managing their fleets effectively with diesel. To drive adoption, the benefits of ERS need to be clearly communicated and demonstrated.

Benediktas Opeikis: Would these criteria change if ERS were introduced? How?

Stakeholder Expert 6: Yes. ERS mitigates range anxiety and reduces the need for large batteries, which in turn improves payload capacity. It also addresses grid capacity issues by distributing the electricity demand more evenly.

Carriers will still prioritize total cost of ownership, vehicle reliability, and infrastructure coverage, but they will also want clarity on how ERS integrates with their operations. Since many carriers already know how to manage their fleets efficiently today, ERS must be seamlessly integrated to be adopted at scale.

Benediktas Opeikis: What measurable indicators could help evaluate these criteria for carriers?

Stakeholder Expert 6: Key indicators include uptime of ERS infrastructure, cost per kilometer, vehicle lifespan, impact on payload, and electricity price stability. Carriers will also evaluate how ERS affects vehicle utilization rates and whether it simplifies or complicates operations.

Vehicle Manufacturers

Benediktas Opeikis: What key factors do manufacturers consider when producing BEHDVs?

Stakeholder Expert 6: First of all, manufacturers must balance vehicle load capacity, battery size, and infrastructure compatibility. Ensuring that vehicles can operate at full load without excessive battery weight is essential.

Infrastructure compatibility is another major concern. Manufacturers must work with infrastructure developers and governments to ensure that ERS and other charging systems are interoperable. The heavy electrical load required for charging means that grid capacity constraints must be addressed.

Benediktas Opeikis: Would their priorities shift if they were to manufacture BEHDVs compatible with ERS?

Stakeholder Expert 6: Yes. ERS could help solve the infrastructure challenge by distributing electricity demand more evenly across the grid, making it easier to secure connections. This allows manufacturers to produce vehicles with smaller, lighter batteries, improving overall efficiency.

Additionally, partnerships with infrastructure developers will become increasingly important. Manufacturers will need to consider when and how to transition their fleets and how to ensure standardization in dynamic charging solutions.

Benediktas Opeikis: What measurable indicators might manufacturers use to assess these criteria?

Stakeholder Expert 6: Manufacturing cost per vehicle, energy efficiency, battery size reduction, and market demand projections. Manufacturers will also track the availability of infrastructure, grid constraints, and regulatory support for ERS.

Grid Operators

Benediktas Opeikis: How do grid operators view ERS adoption?

Stakeholder Expert 6: Grid operators see ERS as an opportunity to distribute electrical demand more evenly. Unlike static charging, which creates peaks in electricity consumption, ERS spreads the demand along roads, improving grid stability.

However, grid operators require more data from carriers and shippers to accurately forecast electricity demand. Predictability is crucial for balancing supply and demand effectively.

Benediktas Opeikis: What indicators are important for grid operators?

Stakeholder Expert 6: Infrastructure availability, electricity demand predictability, and the number of vehicles connected to the system. Additionally, grid operators must assess the return on investment for ERS deployment.

Shippers

Benediktas Opeikis: What are the main considerations for shippers when adopting BEHDVs?

Stakeholder Expert 6: Shippers operate in a low-margin industry, so cost is a major factor. However, CO_2 emissions tracking is becoming increasingly important due to customer demand and regulatory pressure.

Benediktas Opeikis: How might ERS affect their criteria?

Stakeholder Expert 6: ERS could make CO_2 tracking more transparent and improve sustainability reporting. Additionally, a well-established ERS network would make electric transport more cost-effective, making it a more viable option for shippers.

Benediktas Opeikis: What indicators could assess these criteria for shippers?

Stakeholder Expert 6: CO_2 reduction per trip, cost per kilometer, and infrastructure availability. Shippers will also be looking at the predictability of delivery times and how ERS impacts overall logistics efficiency.

Conclusion

Benediktas Opeikis: Across all stakeholders, the business case and infrastructure reliability seem to be common themes. Are there any final insights you'd like to share?

Stakeholder Expert 6: ERS has the potential to be a game-changer for heavy-duty transport, but its success depends on multi-stakeholder collaboration. The industry needs clear regulatory frameworks and financial incentives to encourage early adoption. Additionally, harmonization across countries is crucial for long-haul freight operators to see ERS as a viable solution.

A.7 Stakeholder Expert 7

Date: 7 April 2025
Time: 11:16

Vehicle Manufacturers

Benediktas Opeikis: From the perspective of vehicle manufacturers, what are the main considerations in transitioning to BEHDVs (Battery Electric Heavy-Duty Vehicles), particularly those compatible with Electric Road Systems (ERS)?

Stakeholder Expert 7: Manufacturers are unlikely to scale up production of ERS-compatible trucks without infrastructure certainty. While companies like Scania are exploring this technology, it is still at a prototype stage. For manufacturers, the investment must align with clear infrastructure planning. Smaller batteries enabled by ERS would help reduce vehicle costs and increase demand, but without a functioning ERS network, it remains hypothetical. A holistic approach involving government policy and EU-level coordination is essential to accelerate this transition.

Carriers

Benediktas Opeikis: Shifting to carriers - those owning and operating the trucks - what are their key concerns in adopting BEHDVs?

Stakeholder Expert 7: Their primary concerns are cost and operational efficiency. Current BEHDVs are expensive due to the size of the required batteries needed for long-haul routes. This impacts both investment costs and payload due to the battery weight. In decentralized charging setups, carriers are forced to park and charge for extended periods, reducing utilization and increasing cost. With ERS, the idea is to avoid such inefficiencies by charging during motion, which reduces battery size requirements and eliminates downtime.

Utilization is critical. For instance, a truck might make a single trip in the morning and be used by subcontractors the rest of the day. Electrifying the full day's operation under current conditions is difficult. ERS on major corridors - e.g., Brussels to Rotterdam - would allow carriers to operate all day without large batteries or extended charging stops.

Furthermore, dynamic charging could enable the truck operator to tap into the electricity market when the electricity is cheaper, thus potentially reducing operating costs. This would also benefit the grid as the demand for electricity would be more evenly distributed across the time.

Benediktas Opeikis: Would faster static charging alleviate these issues?

Stakeholder Expert 7: It would help, but battery weight and cost remain problems. More frequent, fast charging requires widespread infrastructure and grid capacity that is currently lacking. We already experience limitations on certain electric routes.

Shippers

Benediktas Opeikis: From the shipper's side - those commissioning the transport- what criteria matter in the transition to BEHDVs or ERS-compatible BEVs?

Stakeholder Expert 7: Shippers are not typically involved in the technicalities of how vehicles are charged. Their focus is on cost and emissions. If electrification provides lower-emission transport without increasing costs or compromising reliability, it is attractive. Whether the electricity is drawn from a plug or an ERS system is not relevant to them.

Grid Operators

Benediktas Opeikis: Let's move to the grid operators. What challenges and opportunities do ERS present from their perspective?

Stakeholder Expert 7: ERS provides a valuable solution for balancing electricity demand. With decentralized charging, there's a risk of grid overload, especially during peak hours. In the Netherlands, for example, grid operators have requested permissions to limit residential charging during evenings.

ERS enables continuous, distributed charging during off-peak hours. This aligns well with renewable energy availability, such as solar energy during the day, which currently cannot always be fed into the grid. Integrating ERS with smart charging mechanisms can stabilize the grid and reduce electricity costs by avoiding peak-time surcharges.

Road Operators

Benediktas Opeikis: And finally, how do you think road operators view the implementation of ERS?

Stakeholder Expert 7: There is currently no strong lobby for ERS among road operators. The visual and structural aspects - such as overhead lines - are often perceived as unattractive or outdated. Different stakeholders along trans-European corridors may have diverging views, which complicates deployment. Therefore, I believe this has to be coordinated and driven at the European level. Without top-down guidance, implementation across multiple jurisdictions would be nearly impossible.

Common Challenges and Opportunities

Benediktas Opeikis: Maybe to conclude, what common trends, challenges, or opportunities do you currently see in the landscape of electric trucks and their dynamic charging capabilities?

Stakeholder Expert 7: One of the key challenges is the fragmented approach to electrification, particularly in the absence of a unified European strategy for ERS deployment. Without a central mandate or coordination, it becomes very difficult to align road operators across borders or even within a single country. Another challenge lies in public perception - ERS infrastructure like overhead lines is often seen as outdated or visually intrusive, which affects political and public support.

That said, there are clear opportunities. Dynamic charging can help solve major issues related to grid congestion by distributing demand over time and geography. It also allows better use of daytime renewable energy, especially solar, which is currently underutilized due to peak production mismatches. To realize these benefits, however, strong leadership and coordination at the EU level will be essential, along with clear technological standardization.

A.8 Stakeholder Expert 8

Date: February 19, 2025

Time: 10:12

Vehicle Manufacturers

Benediktas Opeikis: What factors do vehicle manufacturers prioritize when producing BEHDVs, and how does ERS influence their considerations?

Stakeholder Expert 8: The key priorities for manufacturers revolve around compliance with regulatory emissions targets, market demand, and infrastructure readiness. The EU has set a fleet-level CO_2 emissions reduction target of 40%, which will be costly to ignore.

The primary challenge is that BEHDV adoption remains constrained by inadequate charging infrastructure and high vehicle costs. Manufacturers are cautious about investing in ERS - compatible vehicles unless there is clear infrastructure deployment. Unlike static charging, which is largely driven by market dynamics, ERS deployment is expected to be more under government control, influencing manufacturers' strategies.

Another challenge is the technical standardization of dynamic charging systems. There are multiple competing technologies, and without a clear standard, manufacturers are hesitant to commit. Some are preparing for ERS integration, but it is not yet considered a prerequisite for BEHDV deployment.

Carriers

Benediktas Opeikis: What are the primary considerations for carriers in adopting BEHDVs, and how does ERS factor into their decision-making?

Stakeholder Expert 8: Carriers operate on tight margins, so their top concerns are vehicle cost, operational efficiency, and infrastructure availability. The upfront cost of a BEHDV is approximately two to three times higher than a diesel truck, making TCO a critical factor.

With ERS, carriers could potentially benefit from smaller battery sizes, reducing weight and improving payload capacity. Moreover, dynamic charging eliminates the need for planning lengthy charging stops, thereby increasing vehicle utilization. However, the viability of ERS depends on network density - without sufficient coverage, carriers will hesitate to invest.

Another challenge is driver recruitment and retention. Truck driving is already a demanding job, and adding complex charging logistics increases stress levels. ERS could simplify charging processes, making operations smoother and more predictable. Carriers, however, require reassurance regarding infrastructure reliability before committing to ERS-compatible vehicles.

Shippers

Benediktas Opeikis: What criteria are most important for shippers when considering BEHDVs?

Stakeholder Expert 8: Shippers prioritize cost efficiency, sustainability, and customer expectations. Some major shippers have ambitious CO_2 reduction targets, but many mid-sized and smaller firms remain focused on cost-effectiveness.

A growing number of shippers are exploring ways to monetize charging infrastructure. Some already sell surplus electricity back to the grid, which could make BEHDV adoption more attractive. However, the lack of widespread infrastructure remains a limiting factor. Shippers generally do not care whether a truck charges statically or dynamically, as long as it meets delivery and cost expectations.

Furthermore, some shippers care about the wellbeing of drivers and their working conditions. Similarly, as from the carrier perspective, shippers can claim that they provide good conditions even for external employees who are involved in their supply chain.

Freight Forwarders

Benediktas Opeikis: What factors influence freight forwarders' approach to BEHDV adoption, and how does ERS play into their considerations?

Stakeholder Expert 8: Freight forwarders operate as intermediaries, balancing the needs of shippers and carriers. Their primary concerns include price volatility, efficiency, and regulatory compliance.

One advantage of electrification is the potential stabilization of energy costs. Unlike diesel, which is subject to market fluctuations, electricity can be sourced strategically, reducing financial uncertainty. ERS could further improve cost predictability by distributing electricity demand over time and reducing peak load charges.

Freight forwarders also seek operational efficiency. Dynamic charging could optimize route planning by eliminating the need for extended charging stops. However, a lack of standardization and inconsistent infrastructure deployment across countries complicates the business case for ERS.

Grid Operators

Benediktas Opeikis: What challenges and opportunities do grid operators face in supporting BEHDVs and ERS?

Stakeholder Expert 8: Developing both types of infrastructure is expensive so the number of users utilising the network is the primary criteria for these stakeholders. More users make a better business case that reduces the investment risk.

A major advantage of ERS is its potential to align charging demand with daytime electricity production, particularly from solar power. In Germany, for example, midday electricity prices have already dropped by €0.06 per kWh due to increased solar generation. Dynamic charging allows vehicles to take advantage of these lower costs, improving the TCO equation.

Another challenge is policy consistency. Governments frequently shift priorities between different electrification strategies, creating uncertainty for investors. Establishing dedicated ERS corridors could mitigate this issue by demonstrating feasibility and ensuring regulatory commitment.

Lastly, community support is a must when talking about both charging types. Local communities might not be in favour of having static charging infrastructure built in the existing, expanded, or newly created parking stops. Similarly, dynamic charging technology requiring a pantograph also disturbs the esthetic landscape of the road.

Road Operators

Benediktas Opeikis: What role do road operators play in the adoption of ERS?

Stakeholder Expert 8: Road operators must assess the economic and technical feasibility of integrating ERS infrastructure. Unlike static charging, which requires minimal road modification, ERS entails significant upfront investment and maintenance considerations.

Operators need assurance that ERS will deliver long-term value. In Germany, for example, authorities have successfully managed a 34 km ERS corridor, demonstrating operational reliability. However, broader deployment requires government support to ensure compatibility with existing infrastructure and road management protocols.

Challenges & Opportunities

Benediktas Opeikis: What common trends or challenges could influence the adoption of BEHDVs and ERS?

Stakeholder Expert 8: Three key challenges stand out:

1. **Policy Stability:** Frequent shifts in government priorities create uncertainty. A more consistent approach - such as parallel investment in both static and dynamic charging - could accelerate adoption.
2. **Infrastructure Investment:** Governments and private investors must align on funding models. Public-private partnerships could play a role in financing ERS corridors.
3. **Standardization:** A lack of uniform ERS technology standards hinders progress. Establishing common specifications will be critical for scaling deployment.

A key opportunity is leveraging solar power to align charging demand with low-cost electricity availability. This could significantly improve the economic case for ERS, particularly for long-haul operations.

A.9 Stakeholder Expert 9

Date: February 7, 2025
Time: 08:28

Vehicle Manufacturers

Benediktas Opeikis: What criteria do vehicle manufacturers prioritize when producing BEHDVs, and how does ERS impact these priorities?

Stakeholder Expert 9: Manufacturers generally focus on profitability, customer demand, and infrastructure readiness. The transition to BEHDVs requires substantial investment, and manufacturers need to see clear demand before committing resources. One emerging trend is retrofitting diesel trucks into electric trucks by replacing the internal combustion engine with an electric powertrain.

Dynamic charging introduces additional considerations. If ERS infrastructure is available, manufacturers can reduce battery size, which makes vehicles lighter and more cost-effective. However, they require standardization for planning and assurance that ERS will not be replaced by another technology in a few years. Manufacturers are conservative by nature, and a stable regulatory and technological framework is crucial for long-term investment.

Benediktas Opeikis: How do manufacturers assess the viability of ERS technology?

Stakeholder Expert 9: They look at factors like demand density (i.e., the number of vehicles per year using the infrastructure) and the feasibility of charging while loading and unloading. Infrastructure compatibility is another key factor. If grid capacity is inadequate, widespread adoption of ERS is unlikely. Partnerships with infrastructure developers and grid operators are essential to secure a reliable supply of electricity.

Carriers

Benediktas Opeikis: What criteria do carriers consider when deciding to adopt BEHDVs, and how does ERS change these considerations?

Stakeholder Expert 9: Investment cost is the primary concern. The cost of purchasing BEHDVs is significantly higher than diesel trucks. Weight is another major factor - battery weight reduces payload capacity, so any solution that reduces battery size is attractive.

Carriers also value smooth planning and operational efficiency. Autonomous vehicles will further drive demand for automatic charging solutions, minimizing downtime and optimizing fleet utilization. The lifespan of static charging infrastructure is a concern, as replacing or upgrading charging stations is costly and disruptive.

With ERS, carriers can reduce battery size and eliminate charging stops, leading to increased vehicle utilization. However, the infrastructure must be reliable, and there must be enough vehicles using the system to make it economically viable.

Shippers

Benediktas Opeikis: What factors are most important for shippers when considering BEHDVs?

Stakeholder Expert 9: Price and environmental impact. Shippers operate on tight margins, so cost remains the dominant factor. However, there is growing pressure to reduce CO_2 emissions. Companies aiming for carbon neutrality see BEHDVs as a strategic investment, provided they can be cost-competitive with diesel trucks.

ERS could enhance sustainability by reducing battery production requirements, thereby lowering the overall environmental footprint. However, shippers need visibility on how ERS adoption will impact transport costs before committing to electric transport solutions.

Road Operators

Benediktas Opeikis: What about road operators? What challenges and opportunities do they see?

Stakeholder Expert 9: Road operators are cautious about installing new infrastructure in roads, due to concerns over maintenance, construction disruption, and compatibility with existing utilities. Dynamic charging technologies must minimize construction complexity and avoid interfering with underground pipes or cables. Overhead systems (catenary) require protective barriers and pylons, complicating road layouts. Ground-based systems like ours (Elonroad) or inductive solutions face scepticism, but less so if the installations are modular and maintenance-friendly.

A major opportunity is reducing land-use needs. Static MW chargers require enormous parking areas - potentially football-field-sized hubs every 60 km. ERS avoids this by using existing roadways for charging.

Grid Operators

Benediktas Opeikis: How does ERS impact the grid, and what are the considerations for grid operators?

Stakeholder Expert 9: Grid operators are concerned with peak demand management. Static charging creates concentrated peaks at charging hubs, which require costly and complex upgrades. ERS distributes power demand both over time and along the length of the road, reducing stress on any single grid connection point. Regardless of which final charging technology wins out, grid capacity upgrades along highways are inevitable and should begin now. Grid operators value predictability, distributed load, and investments that allow for flexible deployment of different charging technologies.

Standardization and Technological Maturity

Benediktas Opeikis: How important is standardization for ERS adoption?

Stakeholder Expert 9: Standardization is critical. Currently, there are multiple ERS technologies, including conductive and inductive charging. Without clear standards, manufacturers hesitate to commit to a specific solution. There is ongoing work to standardize voltage levels and onboard equipment to ensure interoperability.

Static charging has already achieved a high degree of standardization, with common protocols such as OCPP and CCS. ERS, however, is still in the early stages, and conflicting interests between different technological approaches are slowing progress. The sooner standardization is established, the easier it will be for stakeholders to invest in ERS-compatible vehicles and infrastructure.

Challenges and Opportunities for Collaboration

Benediktas Opeikis: What are some common goals that multiple stakeholders could pursue together?

Stakeholder Expert 9: One major opportunity is to integrate ERS into existing electrification efforts rather than treating it as a separate technology. Freight forwarders, manufacturers, and infrastructure operators can collaborate to develop shared charging infrastructure. Government incentives can also play a role in de-risking early investments.

Another trend is the emergence of leasing models for BEHDVs, reducing the financial burden on carriers. Some companies are already offering transport capacity as a service, enabling small fleet operators to transition to electric vehicles without large upfront costs.

Benediktas Opeikis: Any final thoughts?

Stakeholder Expert 9: ERS has the potential to address many of the challenges facing BEHDVs, but it requires strong coordination between stakeholders. Governments must take a leading role in infrastructure deployment, while manufacturers need confidence in long-term technological viability. With the right policies and investments, ERS could significantly accelerate the transition to electric freight transport.

A.10 Stakeholder Expert 10

Date: 16 April 2025
Time: 11:04

Vehicle Manufacturers

Benediktas Opeikis: From the manufacturers' point of view, what are the main considerations when producing battery-electric trucks and possibly ERS-compatible ones?

Stakeholder Expert 10: From our side, it doesn't matter how the truck is charged - static, dynamic, or otherwise - as long as the system is consistent and applied across Europe. That consistency is what makes it viable.

We did a project with RWTH Aachen where we took a standard battery-electric truck and equipped it with an add-on pantograph system. The goal was to avoid building a custom truck with proprietary software just for dynamic charging. The result was positive: the truck could run on regular battery power or draw power from overhead lines without compromising its core design. So, for us, ERS is a complementary technology - it should work with existing EV systems.

Benediktas Opeikis: Would a widespread ERS network enable the use of smaller batteries in trucks?

Stakeholder Expert 10: Definitely. That's one of the major benefits. Smaller batteries mean lower cost, less weight, and potentially higher payload capacity. Current long-haul trucks need up to 500 km range, which still doesn't compare to diesel's 4,000 km. But with ERS, you wouldn't need such large batteries. It makes a business case for smaller, cheaper trucks.

Carriers

Benediktas Opeikis: Let's move to the carriers. What criteria are most relevant for them when adopting battery-electric or ERS-compatible trucks?

Stakeholder Expert 10: The business case is everything. Carriers look at TCO. The cost of the truck, the cost of energy, and the infrastructure determine whether the transition is viable. If they can charge at their own depots, sometimes with solar panels, the TCO can be favorable. But public charging is more expensive and harder to plan.

International trips are particularly hard. Static charging infrastructure is still lacking, especially for trucks. Most charging happens in depots. Public chargers are designed for passenger cars and often not accessible to trucks with trailers. And when chargers are accessible, they might not deliver the expected power.

From the positive side, carriers usually appreciate better torque of the electric trucks, these trucks are easier to maintain, they create less vibrations and noise which are beneficial for both - the driver and the surroundings.

With ERS, a lot of this changes. Charging while driving removes the need for charging breaks. It fits naturally with mandatory driver rest periods. It also helps the grid by distributing demand instead of creating peaks. For the carrier, if the price is competitive and infrastructure is reliable, it's a compelling option. Furthermore, smaller battery could potentially reduce the weight of the trucks that currently is one of the electric truck limitations - they can not carry the same weight as regular diesel truck due to weight limitations across Europe.

Benediktas Opeikis: What about charging speed?

Stakeholder Expert 10: MW charging is a hot topic. It's fast, yes, but it creates energy losses, heat, and high infrastructure costs. The legislation allows 4.5 hours of driving followed by a 45-minute rest. If that time can be used to charge the truck sufficiently, the speed becomes less critical. But today, even planning a route with static charging is complicated - parking areas are full, booking isn't possible, and power output is inconsistent.

Grid Operators

Benediktas Opeikis: How does ERS compare with static charging from the grid's perspective?

Stakeholder Expert 10: With static charging, you have power peaks at limited locations. With ERS, demand is distributed along the road. That's a huge benefit. If you spread charging over 10 km of road, you avoid putting excessive strain on one part of the grid. It also aligns better with renewable energy integration and avoids localized overloads.

Shippers

Benediktas Opeikis: Do shippers care about how trucks are charged—whether by plug or dynamically?

Stakeholder Expert 10: Not at all. They care about the cost and the CO_2 footprint. If a truck is zero-emission, that's what matters. Shippers like IKEA might offer to provide charging at their own depots, maybe even at lower prices using solar panels. But how the truck is charged - ERS or static - is irrelevant to them.

Technological Alternatives and Final Remarks

Benediktas Opeikis: Beyond economics, are there any technological advantages of electric trucks?

Stakeholder Expert 10: Yes. The electric motor is far superior to the diesel engine in many ways. It's less complex, produces no noise or vibration, and has better torque from zero. Maintenance is simpler. Diesel engines are highly evolved, but still inherently complicated and polluting. Electric drivetrains are clean and mature. The main issue is the battery: it's heavy, expensive, and sensitive to temperature, and supply chains are heavily dependent on Asia.

Benediktas Opeikis: Are there any issues with payload?

Stakeholder Expert 10: Yes. Batteries reduce payload capacity. European regulation gives you 2 extra tonnes for zero-emission trucks, but it's not enough. You often need 4 tonnes just to compensate for the battery weight. That's a limitation that still needs addressing.

Challenges and Opportunities

Benediktas Opeikis: What's the status of diesel trucks? Are they on their way out?

Stakeholder Expert 10: Not at all. Diesel will still be used for the majority of operations in 2030. Even if one-third of new trucks are zero-emission by then, two-thirds will still be diesel. OEMs continue investing in diesel, though the efficiency gains are marginal now - maybe 2 to 4%. Electric and hybrid trucks are expanding, but diesel isn't disappearing.

Benediktas Opeikis: What kind of policy changes would help the most?

Stakeholder Expert 10: We need harmonization and clarity. Take the EU's VECTO tool: it calculates CO2 emissions from tank to wheel, not well to wheel. So renewable diesel counts the same as fossil diesel for OEMs. That's not helpful. If the policy gave credit for using clean fuels, it would accelerate the shift. Right now, we're penalized even when our customers do the right thing by using biofuels.

Benediktas Opeikis: Thank you! This has been a very comprehensive and valuable conversation.

Stakeholder Expert 10: Great. I'm happy to help. Good luck with your thesis.

A.11 Stakeholder Expert 11

Date: June 4, 2025
Time: 14:05

Grid Operators

Benediktas Opeikis: What are the main priorities and challenges for grid operators when it comes to the electrification of heavy-duty vehicles?

Stakeholder Expert 11: One of the biggest challenges is the lack of sufficient grid connection capacity, especially along motorways. Setting up high-power charging infrastructure requires significant upgrades, which can't be achieved quickly. Planning ahead is crucial. We need to identify early on where and how electrification will happen so we can allocate the necessary capacity.

Benediktas Opeikis: How does ERS compare with static charging in terms of grid impacts?

Stakeholder Expert 11: ERS helps distribute demand over distance and time, which reduces the need to heavily reinforced grid connection points at specific hubs. With dynamic charging, the load is smoother and more predictable. That simplifies integration from a grid planning and operations perspective.

Benediktas Opeikis: Does ERS also simplify planning?

Stakeholder Expert 11: Yes. In some ways it does. Dynamic charging infrastructure is deployed along the road and can often be planned from scratch, which avoids some of the local permitting and layout issues associated with placing large charging hubs. It offers a more controlled and potentially faster way to provide electrification where grid capacity can be more easily made available.

Benediktas Opeikis: What about regulatory challenges?

Stakeholder Expert 11: That's an important point. At the moment, we lack stable and harmonized regulation. We're missing frameworks that define clear responsibilities and clear priorities from the regulators. Without those, it's hard for grid operators to make long-term investment decisions. If ERS was a political priority, and that deployment would happen along certain corridors, we could prepare accordingly. But right now, many actors are still hesitant, and that slows things down.

Benediktas Opeikis: Are there limitations that could slow down implementation?

Stakeholder Expert 11: One is capacity in terms of rollout. The workforce and industrial resources to scale ERS infrastructure are not fully in place. It takes time to build up capabilities. Also, as I mentioned, the regulatory side needs to mature. But overall, ERS helps reduce the pressure on nodes and spreads out the demand, which is valuable.

Benediktas Opeikis: Any closing thoughts on ERS in the context of grid development?

Stakeholder Expert 11: It's a promising option. If developed in coordination with grid operators, it can help us avoid bottlenecks and manage capacity more effectively. But to succeed, it needs to be treated as a priority with clear planning signals. That's currently missing.

Appendix B: Interview Protocol Statement

Interview Protocol and Data Collection Procedure

This research project is part of a master's thesis titled: Comparing Static and Dynamic Charging for Battery Electric Trucks: A Multi-Stakeholder Perspective Using MAMCA

Author: Benediktas Opeikis

Master of Science in Management of Technology

Delft University of Technology

Purpose and Scope

The objective of the interviews was to gather expert insights from industry professionals on the criteria, priorities, and concerns of key stakeholder groups involved in the adoption of Battery Electric Heavy-Duty Vehicles (BEHDVs) and Electric Road Systems (ERS). The responses were used to develop stakeholder-specific evaluation frameworks within a Multi-Actor Multi-Criteria Analysis (MAMCA).

Interview Methodology

A total of eleven semi-structured expert interviews were conducted between January and June 2025. Participants were selected based on their expertise in logistics, vehicle manufacturing, infrastructure, or energy systems. Prior to each interview, participants were provided with a brief overview of the research scope and informed about the relevant stakeholder categories.

Interviews were conducted remotely via Microsoft Teams, using a semi-structured format with open-ended questions. The same two guiding questions were asked in relation to each stakeholder group discussed:

- What specific criteria do you think [stakeholder X] might prioritize when deciding to adopt BEHDVs?
- How might these criteria differ with the adoption of ERS?

Each interview lasted approximately 45-75 minutes and was recorded with the explicit verbal and explicit digital consent of the participant. Participants were also informed that:

- Their participation was voluntary and could be withdrawn at any time without consequence.
- The interview would be recorded solely for transcription and analysis purposes.
- Their responses would be anonymized in the final publication.

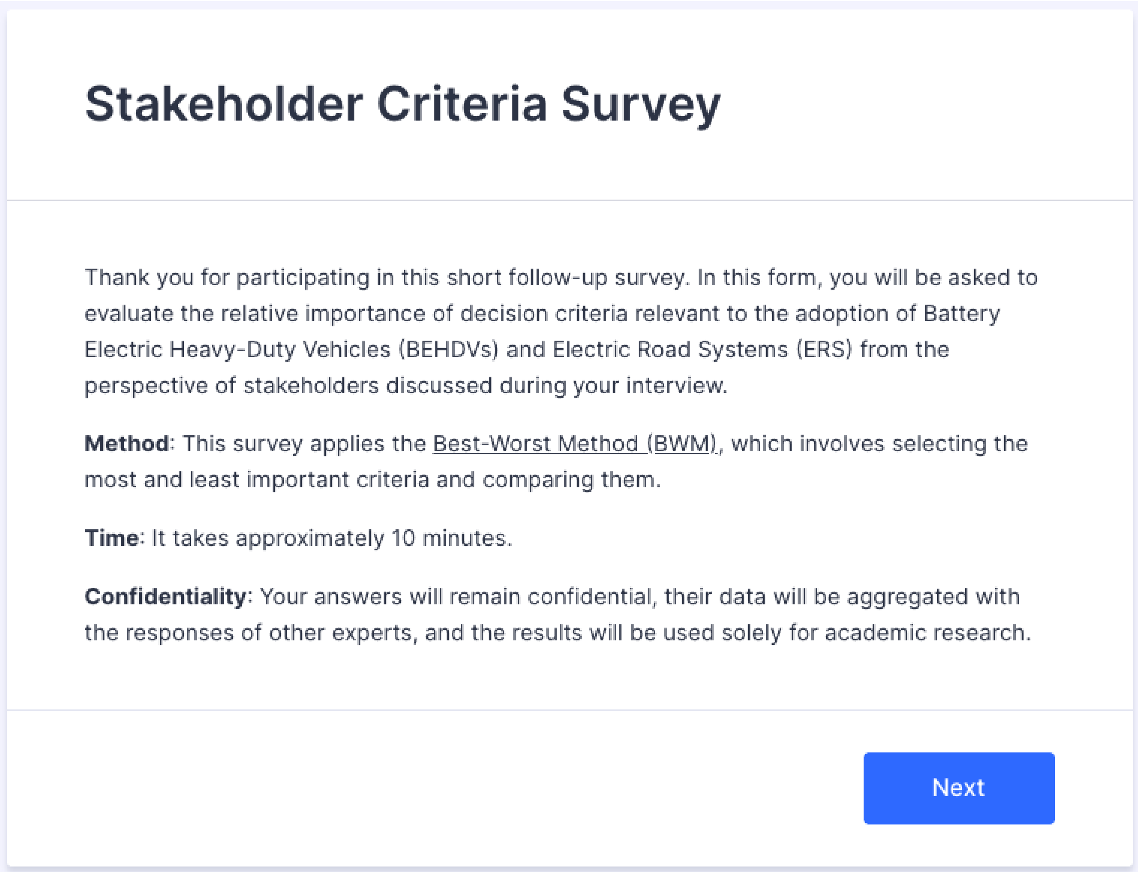
The recordings were transcribed using the integrated Microsoft Teams transcription feature. To start the transcription, every participant needed to explicitly digitally accept that the interview will be transcribed. Each transcript was subsequently edited for clarity and conciseness, and reviewed to ensure that no confidential or identifying information was disclosed without consent. The edited transcripts were later shared with the participants to verify that the interviews were summarized correctly and to allow redaction in case any sensitive information was shared during the interview.

Data Storage, Access and Reuse

All interview raw and edited transcripts are stored securely in institutionally approved, access-restricted digital environments (TU Delft OneDrive). Access to the raw interview data is limited exclusively to the researcher and academic supervisors directly involved in the project. The data is available at request, but it will not be shared, redistributed, or reused for any purposes beyond this thesis without renewed consent from the participants. Retention of identifiable data complies with TU Delft data management and research ethics policies.

Appendix C: Survey for criteria weighting

Every part of the survey that was sent to the industry experts. Some of the experts received only some parts of the questions based on the stakeholders discussed during the earlier interviews. The survey can be accessed here: https://form.jotform.com/251385278674065



Stakeholder Criteria Survey

Thank you for participating in this short follow-up survey. In this form, you will be asked to evaluate the relative importance of decision criteria relevant to the adoption of Battery Electric Heavy-Duty Vehicles (BEHDVs) and Electric Road Systems (ERS) from the perspective of stakeholders discussed during your interview.

Method: This survey applies the Best-Worst Method (BWM), which involves selecting the most and least important criteria and comparing them.

Time: It takes approximately 10 minutes.

Confidentiality: Your answers will remain confidential, their data will be aggregated with the responses of other experts, and the results will be used solely for academic research.

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Shipper Criteria Evaluation

These criteria were identified during the interviews with you and other experts:

- **Cost Efficiency (Freight Rates)** - Ability to maintain competitive pricing while adopting low-emission transport.
- **Sustainability / CO_2 Emissions Reduction** - Contribution of transport operations to emission reduction goals.
- **Reliability of Delivery Schedules** - Ability to ensure timely deliveries when using new vehicle technologies.
- **Well-being of Drivers** - Ensuring safe and fair working conditions for drivers within the supply chain.

Which criteria do you consider the MOST important for Shipper? (Best) *

- ◯ Cost Efficiency (Freight Rates)
- ◯ Sustainability / CO_2 Emissions Reduction
- ◯ Reliability of Delivery Schedules
- ◯ Well-being of Drivers

Which criteria do you consider the LEAST important for Shippers? (Worst) *

- ◯ Cost Efficiency (Freight Rates)
- ◯ Sustainability / CO_2 Emissions Reduction
- ◯ Reliability of Delivery Schedules
- ◯ Well-being of Drivers

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Shippers: Best-to-Others Comparisons

Please rate how much more important the criteria you selected as **Best** (most important) is compared to each of the other criteria.

Use a scale from 1 (equally important) to 5 (much more important).

Cost Efficiency (Freight Rates) compared to Best

1 2 3 4 5

Same importance as Best — Best is much more important

Sustainability / CO_2 Emissions Reduction compared to Best

1 2 3 4 5

Same importance as Best — Best is much more important

Reliability of Delivery Schedules compared to Best

1 2 3 4 5

Same importance as Best — Best is much more important

Well-being of Drivers compared to Best

1 2 3 4 5

Same importance as Best — Best is much more important

- **Cost Efficiency (Freight Rates)** - Ability to maintain competitive pricing while adopting low-emission transport.
- **Sustainability / CO_2 Emissions Reduction** - Contribution of transport operations to emission reduction goals.
- **Reliability of Delivery Schedules** - Ability to ensure timely deliveries when using new vehicle technologies.
- **Well-being of Drivers** - Ensuring safe and fair working conditions for drivers within the supply chain.

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Shippers: Others-to-Worst Comparisons

Now rate how much more important each of the other criteria is compared to the one you selected as **Worst** (Least important).

Use a scale from 1 (equally important) to 5 (much more important).

Cost Efficiency (Freight Rates) compared to Worst

1 2 3 4 5

Same importance as Worst — Cost Efficiency (Freight Rates) is much more important

Sustainability / CO_2 Emissions Reduction to Worst

1 2 3 4 5

Same importance as Worst — Sustainability / CO_2 Emissions Reduction is much more important

Reliability of Delivery Schedules compared to Worst

1 2 3 4 5

Same importance as Worst — Reliability of Delivery Schedules is much more important

Well-being of Drivers compared to Worst

1 2 3 4 5

Same importance as Worst — Well-being of Drivers is much more important

- **Cost Efficiency (Freight Rates)** - Ability to maintain competitive pricing while adopting low-emission transport.
- **Sustainability / CO_2 Emissions Reduction** - Contribution of transport operations to emission reduction goals.
- **Reliability of Delivery Schedules** - Ability to ensure timely deliveries when using new vehicle technologies.
- **Well-being of Drivers** - Ensuring safe and fair working conditions for drivers within the supply chain.

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Carrier Criteria Evaluation

These criteria were identified during the interviews with you and other experts:

- **Total Cost of Ownership (TCO)** - All lifetime vehicle costs including purchase, operation, and maintenance.
- **Operational Reliability** - Avoiding downtime due to infrastructure or technology failure.
- **Vehicle Payload and Weight** - Effect of the vehicle system on transportable cargo weight.
- **Flexibility and Asset Utilization** - Ease of using trucks across contracts and routes.
- **Driver Satisfaction -** Driver comfort, experience, and ease of charging.
- **Access to Infrastructure** - Availability of charging or energy supply infrastructure across relevant transport corridors.

Which criteria do you consider the MOST important for Carriers? (Best) *

- ◯ Total Cost of Ownership (TCO)
- ◯ Operational Reliability
- ◯ Vehicle Payload and Weight
- ◯ Flexibility and Asset Utilization
- ◯ Driver Satisfaction
- ◯ Access to Infrastructure

Which criteria do you consider the LEAST important for Carriers? (Worst) *

- ◯ Total Cost of Ownership (TCO)
- ◯ Operational Reliability
- ◯ Vehicle Payload and Weight
- ◯ Flexibility and Asset Utilization
- ◯ Driver Satisfaction
- ◯ Access to Infrastructure

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Carriers: Best-to-Others Comparisons

Please rate how much more important the criteria you selected as **Best** (most important) is compared to each of the other criteria.

Use a scale from 1 (equally important) to 5 (much more important).

	1	2	3	4	5
Total Cost of Ownership (TCO) compared to Best	Same importance as Best				Best is much more important
Operational Reliability compared to Best	Same importance as Best				Best is much more important
Vehicle Payload and Weight compared to Best	Same importance as Best				Best is much more important
Flexibility and Asset Utilization compared to Best	Same importance as Best				Best is much more important
Driver Satisfaction compared to Best	Same importance as Best				Best is much more important
Access to Infrastructure compared to Best	Same importance as Best				Best is much more important

- **Total Cost of Ownership (TCO)** - All lifetime vehicle costs including purchase, operation, and maintenance.
- **Operational Reliability** - Avoiding downtime due to infrastructure or technology failure.
- **Vehicle Payload and Weight** - Effect of the vehicle system on transportable cargo weight.
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- **Driver Satisfaction** - Driver comfort, experience, and ease of charging.
- **Access to Infrastructure** - Availability of charging or energy supply infrastructure across relevant transport corridors.

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Carriers: Others-to-Worst Comparisons

Now rate how much more important each of the other criteria is compared to the one you selected as **Worst** (Least important).

Use a scale from 1 (equally important) to 5 (much more important).

Total Cost of Ownership (TCO) compared to Worst
1 2 3 4 5
Same importance as Worst — Total Cost of Ownership (TCO) is much more important

Operational Reliability compared to Worst
1 2 3 4 5
Same importance as Worst — Operational Reliability is much more important

Vehicle Payload and Weight compared to Worst
1 2 3 4 5
Same importance as Worst — Vehicle Payload and Weight is much more important

Flexibility and Asset Utilization compared to Worst
1 2 3 4 5
Same importance as Worst — Flexibility and Asset Utilization is much more important

Driver Satisfaction compared to Worst
1 2 3 4 5
Same importance as Worst — Driver Satisfaction is much more important

Access to Infrastructure compared to Worst
1 2 3 4 5
Same importance as Worst — Access to Infrastructure is much more important

- **Total Cost of Ownership (TCO)** - All lifetime vehicle costs including purchase, operation, and maintenance.
- **Operational Reliability** - Avoiding downtime due to infrastructure or technology failure.
- **Vehicle Payload and Weight** - Effect of the vehicle system on transportable cargo weight.
- **Flexibility and Asset Utilization** - Ease of using trucks across contracts and routes.
- **Driver Satisfaction -** Driver comfort, experience, and ease of charging.
- **Access to Infrastructure** - Availability of charging or energy supply infrastructure across relevant transport corridors.

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Vehicle Manufacturers (OEMs) Criteria Evaluation

These criteria were identified during the interviews with you and other experts:

- **Profitability and Customer Demand** - Ensuring product-market fit and sustainable business returns.
- **Infrastructure Readiness** - Alignment between vehicle capabilities and external charging network development.
- **Standardization and Interoperability** - Compatibility of vehicles with widely adopted technical standards.
- **Long-Term Technology Risk** - Uncertainty about which energy technologies will dominate the future market.

Which criteria do you consider the MOST important for Vehicle Manufacturers (OEMs)? (Best) *

- ○ Profitability and Customer Demand
- ○ Infrastructure Readiness
- ○ Standardization and Interoperability
- ○ Long-Term Technology Risk

Which criteria do you consider the LEAST important for Vehicle Manufacturers (OEMs)? (Worst) *

- ○ Profitability and Customer Demand
- ○ Infrastructure Readiness
- ○ Standardization and Interoperability
- ○ Long-Term Technology Risk

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Vehicle Manufacturers (OEMs): Best-to-Others Comparisons

Please rate how much more important the criteria you selected as **Best** (most important) is compared to each of the other criteria.

Use a scale from 1 (equally important) to 5 (much more important).

Profitability and Customer Demand compared to Best	1 Same importance as Best	2	3	4	5 Best is much more important
Infrastructure Readiness compared to Best	1 Same importance as Best	2	3	4	5 Best is much more important
Standardization and Interoperability compared to Best	1 Same importance as Best	2	3	4	5 Best is much more important
Long-Term Technology Risk compared to Best	1 Same importance as Best	2	3	4	5 Best is much more important

- **Profitability and Customer Demand** - Ensuring product-market fit and sustainable business returns.
- **Infrastructure Readiness** - Alignment between vehicle capabilities and external charging network development.
- **Standardization and Interoperability** - Compatibility of vehicles with widely adopted technical standards.
- **Long-Term Technology Risk** - Uncertainty about which energy technologies will dominate the future market.

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Vehicle Manufacturers (OEMs): Others-to-Worst Comparisons

Now rate how much more important each of the other criteria is compared to the one you selected as **Worst** (Least important).

Use a scale from 1 (equally important) to 5 (much more important).

	1	2	3	4	5
Profitability and Customer Demand compared to Worst	Same importance as Worst				Profitability and customer demand is much more important
Infrastructure Readiness compared to Worst	Same importance as Worst				Infrastructure readiness is much more important
Standardization and Interoperability compared to Worst	Same importance as Worst				Standardization and Interoperability is much more important
Long-Term Technology Risk compared to Worst	Same importance as Worst				Long-Term Technology Risk is much more important

- **Profitability and Customer Demand** - Ensuring product-market fit and sustainable business returns.
- **Infrastructure Readiness** - Alignment between vehicle capabilities and external charging network development.
- **Standardization and Interoperability** - Compatibility of vehicles with widely adopted technical standards.
- **Long-Term Technology Risk** - Uncertainty about which energy technologies will dominate the future market.

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Electrical Grid Operators Criteria Evaluation

These criteria were identified during the interviews with you and other experts:

- **Demand Density** - Number of users required to justify infrastructure investment.
- **Distributed Load Management** - Ability to spread electricity demand to avoid grid bottlenecks.
- **Grid Capacity Constraints** - Limitations in local or regional grids to support high charging demand.
- **Policy Stability and Regulatory Support** - Long-term regulatory certainty to enable strategic investment.

Which criteria do you consider the MOST important for Electrical Grip Operators? (Best) *

- ○ Demand Density
- ○ Distributed Load Management
- ○ Grid Capacity Constraints
- ○ Policy Stability and Regulatory Support

Which criteria do you consider the LEAST important for Electrical Grip Operators? (Worst) *

- ○ Demand Density
- ○ Distributed Load Management
- ○ Grid Capacity Constraints
- ○ Policy Stability and Regulatory Support

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Electrical Grid Operators: Best-to-Others Comparisons

Please rate how much more important the criteria you selected as **Best** (most important) is compared to each of the other criteria.

Use a scale from 1 (equally important) to 5 (much more important).

	1	2	3	4	5
Demand Density compared to Best	Same importance as Best				Best is much more important
Distributed Load Management compared to Best	Same importance as Best				Best is much more important
Grid Capacity Constraints compared to Best	Same importance as Best				Best is much more important
Policy Stability and Regulatory Support compared to Best	Same importance as Best				Best is much more important

- **Demand Density** - Number of users required to justify infrastructure investment.
- **Distributed Load Management** - Ability to spread electricity demand to avoid grid bottlenecks.
- **Grid Capacity Constraints** - Limitations in local or regional grids to support high charging demand.
- **Policy Stability and Regulatory Support** - Long-term regulatory certainty to enable strategic investment.

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Electrical Grid Operators: Others-to-Worst Comparisons

Now rate how much more important each of the other criteria is compared to the one you selected as **Worst** (Least important).

Use a scale from 1 (equally important) to 5 (much more important).

Demand Density compared to Worst

1 2 3 4 5

Same importance as Worst — Demand Density is much more important

Distributed Load Management compared to Worst

1 2 3 4 5

Same importance as Worst — Distributed Load Management is much more important

Grid Capacity Constraints compared to Worst

1 2 3 4 5

Same importance as Worst — Grid Capacity Constraints is much more important

Policy Stability and Regulatory Support compared to Worst

1 2 3 4 5

Same importance as Worst — Policy Stability and Regulatory Support is much more important

- **Demand Density** - Number of users required to justify infrastructure investment.
- **Distributed Load Management** - Ability to spread electricity demand to avoid grid bottlenecks.
- **Grid Capacity Constraints** - Limitations in local or regional grids to support high charging demand.
- **Policy Stability and Regulatory Support** - Long-term regulatory certainty to enable strategic investment.

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Road Operators Criteria Evaluation

These criteria were identified during the interviews with you and other experts:

- **Investment and Maintenance Needs** - Cost and effort required to build and maintain new road-integrated systems.
- **Land Use Efficiency** – Minimizing the space required for vehicle charging or energy systems.
- **Public Acceptance and Visual Impact** – Influence of new infrastructure on public perception and landscape aesthetics.

Which criteria do you consider the MOST important for Road Operators? (Best) *

- ○ Investment and Maintenance Needs
- ○ Land Use Efficiency
- ○ Public Acceptance and Visual Impact

Which criteria do you consider the LEAST important for Road Operators? (Worst) *

- ○ Investment and Maintenance Needs
- ○ Land Use Efficiency
- ○ Public Acceptance and Visual Impact

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Road Operators: Best-to-Others Comparisons

Please rate how much more important the criteria you selected as **Best** (most important) is compared to each of the other criteria.

Use a scale from 1 (equally important) to 5 (much more important).

Investment and Maintenance Needs compared to Best

1 2 3 4 5

Same importance as Best — Best is much more important

Land Use Efficiency compared to Best

1 2 3 4 5

Same importance as Best — Best is much more important

Public Acceptance and Visual Impact compared to Best

1 2 3 4 5

Same importance as Best — Best is much more important

- **Investment and Maintenance Needs** - Cost and effort required to build and maintain new road-integrated systems.
- **Land Use Efficiency** – Minimizing the space required for vehicle charging or energy systems.
- **Public Acceptance and Visual Impact** – Influence of new infrastructure on public perception and landscape aesthetics.

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Road Operators: Others-to-Worst Comparisons

Now rate how much more important each of the other criteria is compared to the one you selected as **Worst** (Least important).

Use a scale from 1 (equally important) to 5 (much more important).

Investment and Maintenance Needs compared to Worst

1 2 3 4 5

Same importance as Worst — Investment and Maintenance Needs is much more important

Land Use Efficiency compared to Worst

1 2 3 4 5

Same importance as Worst — Land Use Efficiency is much more important

Public Acceptance and Visual Impact compared to Worst

1 2 3 4 5

Same importance as Worst — Public Acceptance and Visual Impact is much more important

- **Investment and Maintenance Needs** - Cost and effort required to build and maintain new road-integrated systems.
- **Land Use Efficiency** – Minimizing the space required for vehicle charging or energy systems.
- **Public Acceptance and Visual Impact** – Influence of new infrastructure on public perception and landscape aesthetics.

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Freight Forwarders Criteria Evaluation

These criteria were identified during the interviews with you and other experts:

- **Cost Stability and Control (Energy Costs)** - Managing energy costs with lower price volatility than diesel.
- **Operational Efficiency** - Ability to efficiently allocate vehicles and plan routes.
- **Regulatory Compliance and Sustainability Goals** - Meeting emission targets and environmental obligations.
- **Competitive Advantage** - The ability to gain preferential market access and business opportunities by operating compliant zero-emission fleets.

Which criteria do you consider the MOST important for Freight Forwarders? (Best) *

- ○ Cost Stability and Control (Energy Costs)
- ○ Operational Efficiency
- ○ Regulatory Compliance and Sustainability Goals
- ○ Competitive Advantage

Which criteria do you consider the LEAST important for Freight Forwarders? (Worst) *

- ○ Cost Stability and Control (Energy Costs)
- ○ Operational Efficiency
- ○ Regulatory Compliance and Sustainability Goals
- ○ Competitive Advantage

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Freight Forwarders: Best-to-Others Comparisons

Please rate how much more important the criteria you selected as **Best** (most important) is compared to each of the other criteria.

Use a scale from 1 (equally important) to 5 (much more important).

Cost Stability and Control (Energy Costs) compared to Best

1 2 3 4 5

Same importance as Best — Best is much more important

Operational Efficiency compared to Best

1 2 3 4 5

Same importance as Best — Best is much more important

Regulatory Compliance and Sustainability Goals compared to Best

1 2 3 4 5

Same importance as Best — Best is much more important

Competitive Advantage compared to Best

1 2 3 4 5

Same importance as Best — Best is much more important

- **Cost Stability and Control (Energy Costs)** - Managing energy costs with lower price volatility than diesel.
- **Operational Efficiency** - Ability to efficiently allocate vehicles and plan routes.
- **Regulatory Compliance and Sustainability Goals** - Meeting emission targets and environmental obligations.
- **Competitive Advantage** - The ability to gain preferential market access and business opportunities by operating compliant zero-emission fleets.

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Freight Forwarders: Others-to-Worst Comparisons

Now rate how much more important each of the other criteria is compared to the one you selected as **Worst** (Least important).

Use a scale from 1 (equally important) to 5 (much more important).

	1	2	3	4	5
Cost Stability and Control (Energy Costs) compared to Worst	Same importance as Worst				Cost Stability and Control (Energy Costs) is much more important
Operational Efficiency compared to Worst	Same importance as Worst				Operational Efficiency is much more important
Regulatory Compliance and Sustainability Goals compared to Worst	Same importance as Worst				Regulatory Compliance and Sustainability Goals is much more important
Competitive Advantage compared to Worst	Same importance as Worst				Competitive Advantage is much more important

- **Cost Stability and Control (Energy Costs)** - Managing energy costs with lower price volatility than diesel.
- **Operational Efficiency** - Ability to efficiently allocate vehicles and plan routes.
- **Regulatory Compliance and Sustainability Goals** - Meeting emission targets and environmental obligations.
- **Competitive Advantage** - The ability to gain preferential market access and business opportunities by operating compliant zero-emission fleets.

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Appendix D: Survey results consistency ratio (ξ)

The consistency ratio of every response of the survey. The answers were gathered anonymously so there are no names linked to the answers. Road operators had four complete answers that enabled weighting, Freight Forwarders - two, and remaining stakeholders - seven each.

Table D.1: Consistency ratio (ξ) for every survey answer group by the stakeholder.

Answer	Shippers	Carriers	Vehicle Manufacturers	Freight Forwarders	Grid operators	Road operators
1	0.097	0.089	0.091	0.127	0.127	0.114
2	0.102	0.048	0.032	0.052	0.091	0.095
3	0.1	0.022	0.032	-	0.083	0.111
4	0.142	0.129	0.135	-	0.085	0.1
5	0.068	0.062	0.068	-	0.127	-
6	0.098	0.063	0.142	-	0.091	-
7	0.15	0.055	0.075	-	0.065	-
Mean	**0.108**	**0.067**	**0.082**	**0.09**	**0.096**	**0.105**

Appendix E: Weights of the criteria

Table contains all criteria and related stakeholder groups, average weight, standard deviation (SD) of the weight, and coefficient of variation (CV) of the weight. The individual criteria with the highest weight were Cost Efficiency (Freight Rates) for Shippers while the lowest - Driver Satisfaction for Carriers.

Table E.1: Average weight, standard deviation and coefficient of variation of average weight for every criteria.

Stakeholder	Criteria	Average weight	SD	CV
Shippers	Cost Efficiency (Freight Rates)	0.461	0.1	22%
	Sustainability / CO_2 Emissions Reduction	0.209	0.107	51%
	Reliability of Delivery Schedules	0.216	0.127	59%
	Well-being of Drivers	0.115	0.06	52%
Carriers	Total Cost of Ownership (TCO)	0.283	0.052	18%
	Operational Reliability	0.169	0.058	34%
	Vehicle Payload and Weight	0.144	0.029	20%
	Flexibility and Asset Utilization	0.153	0.057	37%
	Driver Satisfaction	0.064	0.022	34%
	Access to Infrastructure	0.187	0.083	44%
Vehicle Manufacturer	Profitability and Customer Demand	0.495	0.07	14%
	Infrastructure Readiness	0.22	0.037	17%
	Standardization and Interoperability	0.171	0.031	18%
	Long-Term Technology Risk	0.114	0.052	46%
Electrical Grid Operators	Demand Density	0.18	0.108	60%
	Distributed Load Management	0.144	0.08	56%
	Grid Capacity Constraints	0.371	0.093	25%
	Policy Stability and Regulatory Support	0.306	0.089	29%
Road Operators	Investment and Maintenance Needs	0.471	0.133	28%
	Land Use Efficiency	0.385	0.17	44%
	Public Acceptance and Visual Impact	0.145	0.063	43%
Freight Forwarders	Cost Stability and Control (Energy Costs)	0.169	0.127	75%
	Operational Efficiency	0.376	0.127	34%
	Regulatory Compliance and Sustainability Goals	0.308	0.192	62%
	Competitive Advantage	0.147	0.062	42%

Appendix F: Survey result variability summary

The interviewed experts agreed the most on the criteria relevant for Vehicle Manufacturers then followed by Carriers. Criteria of Shippers and Electrical Grid Operators had twice higher absolute variation somewhat higher relative variation. Criteria of Road Operators and Freight Forwarders had the highest absolute variation, while Freight Forwarders recorded the highest relative variation as well.

Table F.1: Mean SD and CV for all criteria of the stakeholders.

Stakeholder	Mean SD	Mean CV
Shippers	0.099	46%
Carriers	0.05	32%
Vehicle Manufacturers	0.048	24%
Electrical Grid Operators	0.093	42%
Road Operators	0.122	39%
Freight Forwarders	0.127	53%

Appendix G: Weights based on criteria theme

Table below indicates that Economic and Business Viability criteria are by far the most important for stakeholders. Operational and Technical Performance criteria follow then with lower average standard deviation (SD) and coefficient of variation (CV), meaning that there was higher consensus between the answers. Lastly, Societal and Environmental Consideration criteria with the smallest weight and the highest relative disagreement level due to high CV.

Table G.1: Average weights, standard deviations and coefficients of variation for every theme.

Theme	Criteria	Weight	SD	CV	Mean Weight	Mean SD	Mean CV
Economic and Business Viability	Cost Efficiency (Freight Rates)	0.461	0.1	22%	0.315	0.093	37%
	Total Cost of Ownership (TCO)	0.283	0.052	18%			
	Profitability and Customer Demand	0.495	0.07	14%			
	Demand Density	0.18	0.108	60%			
	Investment and Maintenance Needs	0.471	0.133	28%			
	Cost Stability and Control (Energy Costs)	0.169	0.127	75%			
	Competitive Advantage	0.147	0.062	42%			
Operational and Technical Performance	Reliability of Delivery Schedules	0.216	0.127	59%	0.221	0.079	36%
	Operational Reliability	0.169	0.058	34%			
	Vehicle Payload and Weight	0.144	0.029	20%			
	Flexibility and Asset Utilization	0.153	0.057	37%			
	Access to Infrastructure	0.187	0.083	44%			
	Infrastructure Readiness	0.22	0.037	17%			
	Standardization and Interoperability	0.171	0.031	18%			
	Long-Term Technology Risk	0.114	0.052	46%			
	Distributed Load Management	0.144	0.08	56%			
	Grid Capacity Constraints	0.371	0.093	25%			
	Land Use Efficiency	0.385	0.17	44%			
	Operational Efficiency	0.376	0.127	34%			
Societal and Environmental Considerations	Sustainability / CO_2 Emissions Reduction	0.209	0.107	51%	0.191	0.089	45%
	Well-being of Drivers	0.115	0.06	52%			
	Driver Satisfaction	0.064	0.022	34%			
	Policy Stability and Regulatory Support	0.306	0.089	29%			
	Public Acceptance and Visual Impact	0.145	0.063	43%			
	Regulatory Compliance and Sustainability Goals	0.308	0.192	62%			

Appendix H: Summary of criteria weights and indicators grouped by theme

Table H.1: Criteria grouped by theme, sorted by weight, with their indicators results.

Theme	Stakeholder	Criteria	Weight	BEHDV	BEHDV + ERS	Desirable Direction
Economic and Business Viability	Vehicle Manufacturers	Profitability and Customer Demand	0.495	3	1.5	Higher
	Road Operators	Investment and Maintenance Needs	0.471	0.072 EUR/km	0.048 EUR/km	Lower
	Shippers	Cost Efficiency (Freight Rates)	0.461	0.03 EUR	0.028 EUR	Lower
	Carriers	Total Cost of Ownership (TCO)	0.283	0.629 EUR/km	0.651 EUR/km	Lower
	Electrical Grid Operators	Demand Density	0.18	2	5	Higher
	Freight Forwarders	Cost Stability and Control (Energy Costs)	0.169	0	0.55	Higher
	Freight Forwarders	Competitive Advantage	0.147	4.25	4	Higher
Operational and Technical Performance	Road Operators	Land Use Efficiency	0.385	50-100 m^2/km	7.5-10 m^2/km	Lower
	Freight Forwarders	Operational Efficiency	0.376	3	1.33	Higher
	Electrical Grid Operators	Grid Capacity Constraints	0.371	2.33	4	Higher
	Vehicle Manufacturers	Infrastructure Readiness	0.22	5.67	3.33	Higher
	Shippers	Reliability of Delivery Schedules	0.216	2.33	2.67	Higher
	Carriers	Access to Infrastructure	0.187	3.33	1	Higher
	Vehicle Manufacturers	Standardization and Interoperability	0.171	9	7-8	Higher
	Carriers	Operational Reliability	0.169	16-32%	10-20%	Lower
	Carriers	Flexibility and Asset Utilization	0.153	2.8	1.6	Higher
	Carriers	Vehicle Payload and Weight	0.144	0.52	0.58	Higher
	Electrical Grid Operators	Distributed Load Management	0.144	2	4	Higher
	Vehicle Manufacturers	Long-Term Technology Risk	0.114	4	2.5	Higher
Societal and Environmental Considerations	Freight Forwarders	Regulatory Compliance and Sustainability Goals	0.308	5	5	Higher
	Electrical Grid Operators	Policy Stability and Regulatory Support	0.306	4.5	2	Higher
	Shippers	Sustainability / CO_2 Emissions Reduction	0.209	0 gCO_2/km	0 gCO_2/km	Lower
	Road Operators	Public Acceptance and Visual Impact	0.145	2.75	2.25	Higher
	Shippers	Well-being of Drivers	0.115	3.6	4.2	Higher
	Carriers	Driver Satisfaction	0.064	3.6	4.2	Higher