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BATTERY SWAPPING TECHNOLOGY IN THE ELECTRIFICATION OF TRUCKS

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ABSTRACT

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The electrification of heavy-duty trucks (HDTs) is a key element in the decarbonisation of freight transport. However, existing charging solutions face practical limitations, particularly related to vehicle downtime and increasing pressure on electricity grids. Battery swapping, which enables the rapid replacement of discharged batteries, has therefore gained attention as a possible alternative. This study investigates the current status, feasibility, and potential role of battery swapping in HDT electrification and uses a qualitative, system-level approach. To compare battery swapping with megawatt charging and hydrogen fuel cell technologies, the analysis combines academic and grey literature with expert interviews and a multi-criteria decision analysis (MCDA).

The findings reveal that the global deployment of this technology is characterized by strong regional divergence. In China, battery swapping has reached commercial maturity (TRL 9) and is implemented at scale, supported by standardised vehicle interfaces, coordinated policy support, and high-utilisation logistics operations. In contrast, developments in Europe and North America remain largely confined to pilot and demonstration projects (TRL 4-6). These constraints are shown to arise less from technological limitations than from fragmented original equipment manufacturers (OEMs) standards, limited regulatory prioritisation, and infrastructure planning practices that continue to favour conventional charging solutions.

The results further indicate that battery swapping can offer distinct operational benefits, particularly by minimising downtime and improving grid flexibility through load shifting. These advantages make the technology especially suitable for predictable, high-throughput applications such as ports, logistics hubs, and mining corridors.

At the same time, the MCDA results and the socio-technical analysis informed by the Multi-Level Perspective (MLP) suggest that battery swapping is not universally applicable across all freight contexts. Its broader deployment depends on a high degree of socio-technical alignment, requiring coordination between vehicle design, infrastructure investments, policy frameworks, and user practices. Overall, the thesis presents battery swapping as a context-dependent option and highlights its relevance within the zero-emission freight portfolio in cases where its operational and system-level benefits can be effectively applied.

Keywords: Battery swapping; Heavy-duty trucks; Truck electrification; Zero-emission freight transport; Electricity grid impacts; Socio-technical transitions

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PREFACE

The motivation to undertake this thesis arose from a strong sense of curiosity and a desire to better understand the complex challenges surrounding the electrification of heavy-duty freight transport. Over the course of this research, the thesis evolved beyond a purely academic exercise into a learning journey shaped by diverse perspectives, professional encounters, and meaningful exchanges.

An important part of this work was the opportunity to engage in discussions and interviews with experts and practitioners from academia, industry, and policy-related backgrounds. These conversations not only provided valuable insights into battery swapping and truck electrification but also offered exposure to differing viewpoints shaped by distinct institutional, cultural, and regional contexts. The openness, generosity, and willingness of the interview participants to share their knowledge and experiences created a strong sense of collaboration and support throughout the research process.

The research journey was further enriched through participation in professional and academic events, where direct interaction with industry representatives and researchers provided practical insights into ongoing developments and real-world challenges. These experiences helped bridge academic research with industrial practice and deepened my understanding of the dynamics shaping technological transitions in freight transport.

First and foremost, I would like to express my sincere gratitude to Professor Heikki Liimatainen for his trust, guidance, and academic support throughout this thesis. His encouragement enabled me to explore a field that was initially unfamiliar and to approach it with confidence and intellectual openness. I am also grateful to Erika Kallionpää, for her constructive feedback and thoughtful guidance during different stages of this work.

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LIST OF SYMBOLS AND ABBREVIATIONS

BET	Battery Electric Truck
BEV	Battery Electric Vehicle
BSS	Battery Swapping Station
CapEx	Capital Expenditure
ERS	Electric Road System
FC	Fast Charging
FCET	Fuel Cell Electric Truck
GHG	Greenhouse Gas
HDT	Heavy-Duty Truck
H_2-FC	Hydrogen Fuel-Cell
HFCV	Hydrogen Fuel Cell Vehicle
MCDA	Multi-Criteria Decision Analysis
MCS	Megawatt Charging System
MLP	Multi-Level Perspective
OEM	original equipment manufacturer
TCO	Total Cost of Ownership
TRL	Technology Readiness Level

1 INTRODUCTION

This thesis examines the current status, feasibility, and potential role of battery swapping in the electrification of heavy-duty trucks (HDTs). Throughout this thesis, heavy-duty vehicles (HDVs) refer to medium and heavy-duty freight trucks characterized by high daily energy demand and intensive operational cycles.

This chapter presents: (i) the background and motivation for investigating battery swapping in truck electrification, (ii) the research problem, (iii) the research objectives and questions, (iv) the scope and limitations of the study, and (v) the structure of the thesis.

1.1 Background

Road transport is one of the largest contributors to global greenhouse gas (GHG) emissions (Statista Research Department, 2025). Within this sector, freight transport is responsible for a significant share of road transport emissions, although trucks constitute a relatively small fraction of the total vehicle fleet (International Energy Agency [IEA], 2022b). This imbalance highlights the importance of prioritizing freight transport as a key focus for climate mitigation strategies.

Electrification has emerged as a central pathway for reducing emissions from road transport systems. Over the past decades, however, technological development, policy support, and market uptake of electric vehicles have primarily focused on passenger cars. As a result, the electrification of HDVs has progressed more slowly and remains limited in many regions (Basma & Rodríguez, 2021). The delayed uptake of electric trucks is largely explained by structural and operational challenges that are more severe than those faced in the passenger vehicle segment (IEA, 2022a).

HDTs are characterized by high daily energy demand, long driving ranges, and intensive duty cycles. These characteristics translate into several barriers for battery electric truck (BET) deployment, including limited driving range, long recharging times, high peak power demand, grid congestion risks, and the need for extensive charging infrastructure investments (Larson et al., 2024). In freight operations, vehicle downtime directly affects productivity and operating costs, making energy replenishment time a critical constraint. Consequently, conventional plug-in charging solutions even when supported by high-power charging may not fully satisfy the operational requirements of all freight transport use cases.

Battery swapping has been proposed as an alternative energy replenishment strategy aimed at addressing some of these limitations. Instead of recharging batteries onboard the vehicle, depleted battery packs are exchanged for fully charged ones at dedicated swapping stations. This approach enables rapid energy replenishment, comparable in duration to conventional refuelling, while relocating battery charging processes to station-based operations. Empirical evidence from large-scale deployments in China indicates that battery swapping can reduce energy replenishment times to the order of minutes, whereas charging-based approaches typically require substantially longer durations depending on battery size and charging power, thereby reducing productive operating hours for trucks (Wu et al., 2021; Zhu et al., 2023).

Beyond vehicle-level considerations, battery swapping has also been discussed from an energy-system perspective. As transport electrification accelerates, electricity systems face increasing challenges related to peak demand, grid congestion, and the integration of variable renewable energy sources. High-power fast charging (FC) for HDTs can exacerbate these challenges by introducing large, concentrated loads. Battery swapping is therefore argued to offer additional system-level flexibility, as batteries can be charged more slowly and scheduled during off-peak periods, potentially improving grid compatibility compared with direct high-power charging solutions (Vallera et al., 2021).

Despite its conceptual advantages, the development and deployment of battery swapping for HDTs have progressed unevenly across regions. Large-scale commercial deployment has been observed primarily in a limited number of markets, most notably China, while other regions such as Europe, North America, and Australia remain at pilot or exploratory stages. Differences in market structures, policy frameworks, standardisation practices, electricity prices, and freight operation patterns are commonly reported as contributing factors to this regional divergence, raising questions regarding the transferability of observed successes across contexts.

Accordingly, battery swapping should not be understood solely as a technical solution, but rather as a system innovation that requires coordinated developments across vehicle design, infrastructure provision, electricity systems, and market organisation. From a socio-technical transition perspective, the diffusion of battery swapping involves interactions between emerging technological innovations, established transport and energy systems, and broader policy and market environments. Understanding its potential role in truck electrification therefore requires an integrated assessment that considers technical feasibility, economic performance, grid implications, and regional deployment conditions. This perspective forms the foundation for the analysis conducted in this thesis.

1.2 Problem Statement

Despite growing interest in battery swapping as a potential solution for HDT electrification, its role within the broader transition toward zero-emission freight transport remains insufficiently understood. Existing studies suggest that battery swapping can significantly reduce vehicle downtime and offer operational advantages for high-utilisation freight vehicles; however, these benefits are highly context-dependent and vary across regions, operational settings, and market structures (Wu et al., 2021; Zhu et al., 2023).

A central challenge lies in the fragmented nature of the existing body of knowledge. Much of the literature examines battery swapping from isolated perspectives, such as vehicle-level technical feasibility, station-level operational performance, or country-specific economic evaluations. While these studies provide valuable insights, integrated and systematic analyses of the interdependencies between vehicle design, infrastructure provision, electricity grid integration, and institutional arrangements remain limited (Vallera et al., 2021; Zhu et al., 2023). As a result, it remains unclear under which conditions battery swapping can be considered a viable and scalable pathway for HDT electrification.

At the same time, alternative decarbonisation pathways for freight transport, most notably high-power FC solutions and H_2-FC trucks are advancing rapidly and increasingly shaping policy strategies and infrastructure investments. However, integrated and cross-technology comparisons that explicitly evaluate battery swapping alongside FC and hydrogen-based options across multiple dimensions, including technology readiness, cost structures, grid impacts, and operational suitability, remain limited in the existing literature (Basma & Rodríguez, 2021; Larson et al., 2024).

From a socio-technical transition perspective, this challenge extends beyond technical performance alone. Battery swapping represents an emerging innovation that must interact with established transport and energy systems, as well as broader policy, market, and regulatory environments. Barriers related to standardisation, business models, infrastructure coordination, and grid access may constrain diffusion even when technical feasibility has been demonstrated (Vallera et al., 2021). These socio-technical dynamics are rarely addressed in an integrated manner within current studies.

Consequently, the core problem addressed in this thesis is the absence of a comprehensive, system-level assessment of battery swapping for HDTs that simultaneously considers technological maturity, economic viability, electricity grid implications, and its relative position among competing zero-emission pathways. Without such an integrated perspective, it remains difficult to determine whether battery swapping should be understood as a niche solution for specific applications or as a potentially scalable component of future freight transport systems.

This thesis addresses this problem by synthesising peer-reviewed literature, grey reports, documented case studies, and empirical evidence, supported by structured comparative analysis, to evaluate the current status and possible role of battery swapping in HDT electrification across different regional and operational contexts.

1.3 Research Objectives

Based on the research problem outlined above, the following research objectives are defined. Specifically, the thesis pursues the following objectives:

1. To examine the current global status and deployment patterns of battery swapping for HDTs, with attention to regional differences, maturity levels, and application contexts.

2. To identify and classify the main battery swapping technology configurations available for HDTs and assess their respective technology readiness levels (TRLs).
3. To analyse the economic characteristics of battery swapping systems and identify key cost drivers and operational conditions influencing economic viability.
4. To assess the implications of battery swapping for the electricity system, particularly regarding peak demand, grid congestion, load management, and system-level flexibility.
5. To compare battery swapping with alternative decarbonisation pathways for heavy-duty freight transport, notably FC and hydrogen fuel cell technologies, using a multi-dimensional perspective.
6. To situate battery swapping within a broader socio-technical transition perspective, examining how interactions between technologies, systems, and institutional conditions shape diffusion and scalability.

1.4 Research Questions

To address the research problem and achieve the objectives outlined in the previous section, this thesis is guided by the following research questions:

RQ1: What is the current status and possible role of battery swapping technology in the electrification of HDTs?

RQ2: What battery swapping technologies are available for HDTs?

RQ3: What are the technology readiness levels (TRL) of the identified battery swapping technologies?

RQ4: What are the costs associated with battery-swappable trucks and the required swapping infrastructure?

RQ5: What are the implications of battery swapping for the electricity grid, particularly in terms of peak demand, grid congestion, and load management?

RQ6: How does battery swapping compare with alternative zero-emission pathways for HDTs, including FC and hydrogen fuel cell technologies?

1.5 Overview of Research Methodology

This thesis adopts a qualitative, system-oriented research approach. The study relies on a structured synthesis of existing knowledge rather than primary quantitative modelling or experimental testing. A systematic review of peer-reviewed academic literature is complemented by the analysis of grey literature, documented case studies, and semi-structured expert interviews. Comparative evaluation is supported by a multi-criteria decision analysis (MCDA), while grid-related implications are examined through a qualitative, system-level assessment drawing on reported modelling results. A socio-technical transition perspective is adopted as an interpretive framework. Detailed methodological procedures are presented in Chapter 3.

1.6 Scope and Limitations

This thesis focuses on battery swapping as an energy replenishment pathway for the electrification of heavy-duty freight trucks. The scope of the study is deliberately defined to ensure analytical depth while maintaining relevance to real-world freight transport applications. Heavy-duty vehicles (HDVs) are considered as medium- and heavy-duty trucks used in commercial freight operations, particularly in contexts characterised by high daily energy demand, intensive duty cycles, and limited tolerance for vehicle downtime.

The analysis adopts a system-level perspective on battery swapping, encompassing vehicle-battery architectures, swapping station configurations, operational characteristics, and interactions with the electricity grid. Both technological and non-technological dimensions are examined, including technology readiness levels (TRLs), cost structures, grid implications, and institutional and market-related factors influencing deployment. Battery swapping is evaluated in comparison with alternative zero-emission pathways for heavy-duty trucks, notably high-power FC solutions and hydrogen fuel cell technologies.

Geographically, the thesis adopts an international perspective, drawing on evidence from multiple regions, including China, Europe, North America, and Australia, where battery swapping initiatives for heavy-duty vehicles have been documented. The analysis does not aim to provide exhaustive national-level assessments; instead, it seeks to identify broader patterns, enabling conditions, and contextual differences that shape the feasibility and scalability of battery swapping across regions.

Methodologically, the study is based on a synthesis of peer-reviewed academic literature, grey literature, documented case studies, and empirical evidence. The research does not involve primary quantitative modelling of vehicle performance or power system operation. Instead, it assesses grid-related implications through scenario-based analysis and by drawing on existing modelling results and empirical findings reported in the literature to support comparative and system-level evaluation.

Several limitations should be acknowledged. First, the availability and transparency of data on battery swapping infrastructure costs, operational performance, and utilisation rates vary considerably across regions and projects. This constrains the comparability of reported results and requires cautious interpretation. Second, the rapidly evolving nature of battery technologies, charging standards, and hydrogen infrastructure means that some findings may become outdated as technologies and policy frameworks continue to develop. Third, differences in electricity prices, regulatory environments, freight operation patterns, and market structures limit the direct transferability of results between regions.

In addition, the multi-criteria decision analysis (MCDA) applied in the study is subject to inherent limitations related to the selection of criteria, weighting assumptions, and the number of expert evaluators involved. While the MCDA provides a structured basis for comparing alternative electrification pathways, the results should be interpreted as indicative rather than definitive and may be sensitive to the perspectives of the participating assessors.

Finally, while the thesis adopts a socio-technical perspective to interpret the diffusion of battery swapping, it does not apply a formal quantitative transition model. Instead, socio-technical concepts are used as an analytical lens to structure interpretation and discussion. Despite these limitations, the defined scope enables a robust and integrated assessment of battery swapping as a potential component of future zero-emission freight transport systems.

1.7 Structure of the Thesis

This thesis is structured into six chapters.

Chapter 1 introduces the research topic by outlining the background and motivation, defining the research problem, objectives, and research questions, and specifying the scope and limitations of the study.

Chapter 2 presents the literature review and theoretical background. It reviews existing research on truck electrification, battery swapping technologies, TRLs, cost structures, electricity grid implications, and alternative zero-emission pathways, including FC and H_2-FC trucks. The chapter also introduces relevant socio-technical concepts that inform the analytical perspective of the thesis.

Chapter 3 describes the research methodology. It explains the overall research design, data sources, and analytical methods employed, including the systematic review of academic and grey literature, case study analysis, and the comparative assessment framework used to address the research questions.

Chapter 4 presents the findings of the study. The chapter reports results related to the current status of battery swapping, available technologies and their readiness levels, cost characteristics, electricity grid implications, and comparisons with alternative refuelling and propulsion pathways.

Chapter 5 discusses the findings in relation to the research objectives and broader socio-technical and policy contexts. The chapter interprets the results, highlights key implications for stakeholders, and reflects on regional differences and transition dynamics.

Chapter 6 concludes the thesis by summarizing the main findings, answering the research questions, discussing the overall contribution of the study, and outlining limitations and directions for future research.

2 THEORETICAL BACKGROUND

In this chapter the current academic and industrial discussions on the electrification of trucks will be explored. Of particular interest is battery swapping technology.

The chapter is divided into several main sections, beginning from the history of truck electrification to an elaboration on battery swapping systems. Then swapping is compared with other electrification technologies such as FC, hydrogen fuel cells, and electric roads. Following this, technology readiness, economic viability, and grid infrastructure impacts will be explored. The chapter concludes by indicating some existing research gaps and proposing some areas of future work.

2.1 Background on Truck Electrification

The history of electric trucks dates back to the end of the 19th century. The early electric motor vehicles often used for short-distance urban deliveries. They could reach speeds of 50 km/h, and their range was around 60 kilometers. With the advent of internal combustion engines in the early 20th century, electric trucks remained dormant in the trucking sector. Again, from the beginning of 2000s, technological advancements in batteries and stricter emissions regulations due to increasing concerns about emission reduction brought renewed attention to electrification (Łebkowski, 2017).

Despite accounting for only around 9% of the global vehicle stock and approximately 17% of total vehicle miles driven, freight trucks are responsible for a disproportionately high share of life-cycle road vehicle GHG emissions, estimated at around 39% (Aryanpur & Rogan, 2024). Freight trucks released 5% of all transportation-related CO_2e emissions into the environment in 2023, according to World Economic Forum (2024). For these reasons political policies have increasingly focused on BETs.

Despite all benefits, truck electrification comes with several challenges. Data from China shows that HDTs compare with their diesel counterparts are in less use and this is due to range anxiety and charge limitations (Zhao et al., 2024). For example, insufficient charging and battery swapping infrastructure in cities like Chengdu has been a barrier to HDT electrification (Liu & Deb, 2024).

2.2 Battery Swapping and Competing Technologies

As the electrification of heavy-duty road transport accelerates, several technological pathways have emerged to replace diesel-powered trucks. Each alternative offers distinct advantages and faces specific challenges regarding operational flexibility, charging time, infrastructure requirements, and cost. Understanding these technologies is essential to position battery swapping within the broader context of truck electrification. The main competing and complementary developments include FC systems (such as the Megawatt Charging System (MCS)), H_2-FC trucks, electric road systems (ERS), and conventional overnight charging solutions.

Overnight charging: In this method electric vehicles charge while they are parked in overnight depots or parking spaces where the demand of electric power is lower or the capacity of the grid is underutilized. This is a viable method for fleets with regular predictable schedules and long parking periods, such as municipal service vehicles, public transport buses, and urban delivery trucks. Overnight charging can reduce the infrastructure costs by reducing the number of charging points and benefit from cheaper electricity through off-peak pricing (Hildermeier et al., 2025).

Fast charging: FC refers to plug-in charging solutions that deliver high-power electricity directly to the batteries of electric vehicles. For heavy-duty electric trucks, FC times vary widely depending on battery capacity, charging power, and the targeted state of charge. While partial FC can be achieved within tens of minutes under high-power DC conditions, full charging may take several hours when lower charging powers are used (Bhardwaj & Mostofi, 2022).

Such charging durations can result in significant operational downtime, which is particularly relevant for fleet logistics operators engaged in fleet optimisation and delivery scheduling. Moreover, FC events often occur during peak operating hours, when multiple trucks may charge simultaneously, thereby placing substantial strain on the electricity grid (Wang et al., 2025).

According to the International Council on Clean Transportation (ICCT), charging infrastructure for heavy-duty BETs is evolving, with current public fast chargers typically in the 150-350 kW range, and megawatt-class (e.g., ~750 kW and above) chargers expected to play a role in future deployments for rapid charging during operational breaks; however, large-scale infrastructure deployment continues to face high costs and grid upgrade challenges for HDT electrification (Bernard et al., 2022).

Battery-electric HDTs tend to have higher upfront purchase costs due in large part to the large onboard battery packs required to support extended driving range and FC needs, which also implies greater material demand and increased vehicle weight. Although the operational electricity cost per kilometer can be relatively low because of the high efficiencies of electric drivetrains, the economics of these systems remain sensitive to peak electricity pricing and grid tariff structures (Basma & Rodríguez, 2023).

In response to these challenges, the MCS, developed under the CharIN initiative, defines a dedicated technical standard for ultra-high-power charging of heavy-duty electric vehicles (CharIN, 2025). The MCS is designed to enable charging capacities of up to approximately 3.75 MW and is widely expected to become the dominant charging standard for long-haul BETs, supported by emerging policy alignment in Europe, including the Alternative Fuels Infrastructure Regulation (AFIR).

From an infrastructure perspective, FC for HDTs requires substantial upfront investment, including high-capacity grid connections, transformers, and power electronics, and often necessitates grid reinforcement at charging locations (Bernard et al., 2022). These requirements can increase both capital expenditure (CapEx) and installation lead times, particularly for corridor-based long-haul applications.

Hydrogen Fuel Cell Vehicles (HFCVs): In freight transport, H_2-FC trucks are increasingly considered as a promising technological possibility for decarbonization especially for long-haul applications (World Economic Forum, 2024). Typical hydrogen refuelling times for HDTs are in the range of 10-15 minutes, resulting in relatively low operational downtime compared with battery-based charging solutions (Otto et al., 2024).

From an operational perspective, H_2-FC trucks offer potentially higher payload capacity and operational flexibility, since onboard hydrogen storage systems tend to be lighter than the large battery packs required for equivalent range in BETs (Qiao, 2024). However, their economic performance is strongly dependent on utilisation rates and hydrogen supply costs, and current operational expenditure for H_2-FC trucks in most regions remains higher than that of BETs, particularly due to the relatively high cost of hydrogen fuel and fuel cell components (Magnino et al., 2024).

In most regions, the operational expenditure of H_2-FC trucks remains substantially higher than that of battery-electric trucks, reflecting the combined effects of high hydrogen fuel prices, immature supply chains, and the additional costs associated with fuel cell systems (Müller, 2025). According to the findings of Tian et al. (2025), hydrogen has a strategic role in areas that are rich in renewable energy. Sgaramella et al. (2024) note that the high utilization rates can improve competitiveness, although there would be yet the barrier of high infrastructure costs.

From an infrastructure perspective, hydrogen refuelling stations for HDTs require very high capital investment, including hydrogen production or delivery systems, high-pressure storage, compression equipment, and extensive safety systems, making them among the most capital-intensive refuelling solutions for heavy-duty road transport (Sgaramella et al., 2024).

HFCVs offer advantages in terms of payload capacity and operational flexibility due to their longer range and shorter refuelling times. However, compared with battery-electric trucks, they face significant economic barriers and lower levels of social and market acceptance. Battery-electric trucks are expected to reach initial cost parity with diesel vehicles earlier than fuel cell trucks, while H_2-FC trucks continue to exhibit higher upfront vehicle costs. These higher costs are largely driven by the expense of fuel cell stacks, high-pressure hydrogen storage tanks, and associated balance-of-plant components (Müller, 2025; Basma & Rodríguez, 2023; Basma & Rodríguez, 2021). Nevertheless, fuel cell trucks could outperform in terms of total cost of ownership for long-haul operations if infrastructure expands and targeted incentives continue.

The interaction between H_2-FC trucks and the electricity system is largely indirect. When hydrogen is produced via electrolysis, electricity demand is shifted upstream to hydrogen production facilities, meaning that the overall grid impact depends strongly on the hydrogen production pathway and the timing of electricity use (IEA, 2019; 2023).

From an environmental perspective, the lifecycle GHG emissions of H_2-FC trucks vary substantially depending on the hydrogen supply chain, with fossil-based hydrogen associated with high emissions, while renewable hydrogen pathways can significantly reduce climate impacts but remain constrained by cost and limited availability (Müller, 2025; Basma & Rodríguez, 2023; Nykvist & Olsson, 2021).

Recent developments in China illustrate the potential scalability of hydrogen fuel cell trucks under strong policy support. By early 2024, several thousand fuel cell trucks were in operation nationwide, and China had initiated a cross-regional hydrogen freight corridor of approximately 1,150 km, demonstrating that large-scale hydrogen-based trucking is technically feasible when supported by coordinated infrastructure deployment (Xinhua/Chinese Government, 2025; Yicai Global, 2024). At the same time, deployment levels and policy support for H_2-FC trucks remain highly uneven across regions, with many markets still limited to pilot projects and early commercial demonstrations. (Basma & Rodríguez, 2021; Hydrogen Council, 2024)

Electric Road Systems (ERSs): ERSs are technologies that allow vehicles to charge dynamically during movement. For ERSs there are different types of technological devices. One is Overhead Catenary Systems (OCS) which represents an alternative electrification solution where trucks are powered via pantographs connecting to overhead electrical wires, like systems used in trolleybuses and trams. These systems are mostly appropriate for High-volume freight transport routes, where intensive usage can justify considerable amounts of investments (Ramshankar et al., 2023). ELISA, FESH, and eWayBW pilot projects in Germany have shown that hybrid trucks on electrified highways are technically viable (Jöhrens et al., 2022). Overhead catenary vehicles (CVs) showed the lowest total cost of ownership (TCO) in the long run when utilized at full capacity (Speth & Funke, 2021). Nevertheless, due to the need for extensive public infrastructure, ERSs are unsuitable for niche or early-stage operations (Gnann et al., 2023).

Inductive ERS (Wireless) is another technology by which energy is transferred wirelessly to vehicles that receive power via coils embedded under the road surface. Smartroad Gotland project in Sweden is among pilot induction systems on a public road for HDTs (Gustavsson et al., 2020). In addition, in conductive rails in a road surface electricity is delivered via rails embedded in or mounted on the road surface and transferred to the vehicle through a physical contact device called a pickup. Evolution Road in Lund, Sweden, for city buses is an example for this technology (Gustavsson et al., 2020). Seamless dynamic charging, as feasibility studies and pilot tests on light-duty electric vehicles demonstrated, is technically possible. However, its actual implementation is still limited due to the high costs of infrastructure and complexity of the technology (Nguyen et al., 2024).

Battery swapping: Battery swapping is an innovative technology that provides quick turnaround capabilities which is crucial for maintaining efficiency in truck operations. In a battery swap process, depleted batteries are replaced with fully charged ones in just a few minutes. This scenario was first introduced in 1896, to overcome the limitations posed by range to early electric vehicles. Commercially, this idea was implemented in the early 1900s by the Hartford Electric Light Company, where customers could buy electric trucks without the batteries from General Vehicle Company and then lease the pre-charged batteries from Hartford Electric. The system allowed users to swap out the depleted batteries for fully charged ones while paying for only the consumed electricity (Ban et al., 2019). this method enormously reduces the energy replenishment period to less than 10 minutes (Bhardwaj & Mostofi, 2022).

Battery swapping also provides high operational flexibility for fleet operators, as vehicle operation is decoupled from battery charging and batteries can be charged independently according to operational and logistical requirements (Nykvist & Olsson, 2021). In terms of infrastructure, BSSs require dedicated facilities, automated or robotic handling systems, and an inventory of battery packs, resulting in relatively high station-level CapEx compared with conventional plug-in charging points (Bhardwaj & Mostofi, 2022). However, this infrastructure is typically centralised and modular, enabling system scalability through incremental expansion of battery inventory rather than proportional increases in grid connection capacity (Nykvist & Olsson, 2021).

Battery swapping has important implications for electricity grid interaction. By enabling batteries to be charged during off-peak periods, battery swapping systems can reduce peak electricity demand at the point of vehicle operation and act as a buffer between freight activity and the power grid (Wang et al., 2024; Zhu et al., 2022). From a cost perspective, battery swapping enables alternative business models such as battery leasing or battery-as-a-service, which can reduce the upfront purchase cost of heavy-duty electric trucks by shifting battery-related CapEx from vehicle owners to service providers (Nåbo et al., 2024; Li et al., 2024). From an environmental perspective, battery swapping systems can reduce the average battery capacity required across a fleet by optimising battery utilisation, which may lower material demand and lifecycle environmental impacts compared with BETs relying on very large onboard battery packs (Wang et al., 2025; Zhu et al., 2023).

Regarding technological maturity, battery swapping for HDTs has reached commercial deployment at scale in some regions, while in others it remains limited to pilot projects and early-stage demonstrations, reflecting differences in policy support, market structures, and standardisation efforts (Li et al., 2024; Nåbo et al., 2024; ACEEE, 2025).

In summary, various technologies are shaping the electrification of heavy-duty road transport, each addressing different operational and infrastructural needs. Overnight depot charging provides a cost-effective option for fleets with predictable routes, while fast and megawatt charging enable higher operational flexibility but require significant grid capacity and investment. H_2-FC trucks offer longer range but face infrastructure and cost challenges, whereas ERSs demonstrate efficiency yet depend on large-scale public infrastructure. Within this evolving technological landscape, battery swapping has gained attention as a complementary and transitional solution that can minimize downtime and reduce peak grid loads by enabling off-peak charging cycles. As highlighted by IEA (2024), future truck electrification will rely on a portfolio of co-existing solutions rather than a single dominant one; within this mix, battery swapping can act as a complementary bridging option.

2.3 Economic Viability and Cost Structure

Recent cost assessments by the Intergovernmental Panel on Climate Change (IPCC, 2023) and the International Transport Forum (ITF, 2022) highlight that the total cost of decarbonising HDTs varies substantially across technologies. While battery-electric trucks show the highest upfront investment for batteries and charging infrastructure, they benefit from lower operational and maintenance costs compared to diesel. H_2-FC trucks, in contrast, face the greatest uncertainty due to high hydrogen production and distribution expenses, which may keep their total cost of ownership above that of battery-electric options well into the 2030s (Basma et al., 2023). ERS could become cost-effective only in high-utilisation freight corridors but require massive upfront public investment, estimated at €1.1-1.6 million per lane-kilometer (ITF, 2022).

Within this landscape, battery swapping represents a mid-cost and more flexible pathway. It allows centralized charging, efficient asset utilization, and separation of battery ownership from vehicles, which can reduce cost uncertainty through shared battery fleets and predictable energy management (IPCC, 2023; ITF, 2022). Previous studies indicate that operational cost efficiency in battery swapping is highly sensitive to utilisation rates and pricing mechanisms, with dynamic pricing approaches potentially reducing lifecycle costs (Celtek et al., 2025). Optimisation studies further demonstrate that combining battery swapping with partial and nonlinear charging decisions can significantly reduce operational costs and downtime in high-utilisation environments such as ports, although swapping entails higher station-level costs (Han et al., 2023). These characteristics make battery swapping particularly relevant for fleet-based logistics operations where downtime, infrastructure intensity, and capital risk must all be minimized simultaneously.

Although considerable advancements have been made in battery swapping technology, several challenges remain a major barrier. High setup costs are among the most important ones. These costs are estimated between $1 million and $1.5 million per site, primarily due to the high battery energy storage requirement (Bernard et al., 2022). Encouraging wide-scale adoption requires strategies such as innovative financing models and government incentives including subsidies and support which should be employed (ACEEE, 2025).

Battery swapping enables fast energy replenishment, reducing downtime to just 5-10 minutes (F. Wang et al., 2025). It also lowers the capital cost of trucks by introducing Battery-as-a-Service (BaaS), where battery ownership is separated from vehicle ownership (Liu, 2024). Some studies indicate that battery swapping outperformed FC and even diesel trucks in situations that the utilizations exceed 43% and speed higher than 32 km/h (Zhu et al., 2023).

Battery degradation can also be accelerated if there is no proper thermal and charge management, although state-of-the-art battery management systems help to lessen the fast-degradation effect (Deng et al., 2023). In addition, grid stress is a relevant topic, especially during peak charge, which could be solved at least partially through smart scheduling and energy storage systems (Zhu et al., 2022).

Among some of the most dynamically development-promoting but underexplored challenges are insuring and holding liability for battery-swapping systems in trucks. Where battery ownership is separated from the ownership of the vehicle, as in BaaS-type models, liability for faults, malfunctions, or issues with performance in batteries become highly complex. The traditional insurance models rarely provide very straightforward provisions for these kinds of ownership arrangements, which may, indeed, hamper the broader adoption of such solutions as battery swapping to be used by truckers.

To date, insurance-related risks associated with battery swapping in HDTs have not been explicitly examined in the academic literature. Existing studies on battery swapping predominantly focus on technical performance, operational characteristics, infrastructure requirements, grid interaction, and economic feasibility (Li et al., 2024; Zhu et al., 2022; Nåbo et al., 2024), while insurance, liability, and regulatory aspects remain largely unexplored. Nevertheless, industry-level evidence indicates that repair complexity and insurance costs for electric vehicles are increasing, which may indirectly affect the trucking sector. For example, industry reporting highlights rising insurance premiums and increasing repair complexity as emerging challenges within the electric vehicle ecosystem, with most evidence currently focused on passenger EVs (Anshul, 2026). Similar concerns regarding elevated repair costs and insurance implications have been identified by major insurance and reinsurance stakeholders, suggesting potential relevance for commercial vehicle applications as well (Swiss Re Institute, 2023; Allianz Global Corporate & Specialty, 2020).

The limited availability of focused academic research on insurance-related risks in the context of battery swapping therefore points to a growing need for targeted studies to support the development of appropriate regulatory and insurance frameworks for battery swapping systems in the HDT sector.

Taken together, the literature indicates clear trade-offs across operational downtime, grid impact, infrastructure and vehicle CapEx, environmental footprint, and technology maturity the criteria that will be formalized in the MCDA.

2.4 Implications of Battery Swapping for the Electricity Grid

Battery swapping offers the flexibility of controlled, centralized battery charging away from peak hours, thereby being less disruptive to the electricity grid than megawatt charging or dynamic charging systems. At swapping stations, batteries are charged at lower power and over longer durations, decoupling the charging process from the vehicle’s arrival time. This approach reduces the instantaneous power draw and stabilizes overall grid load (Wang, Chen, & Hu, 2024).

According to Wang, Chen, & Hu (2024), direct high-power charging clusters for heavy-duty electric vehicles can create localized megawatt-scale loads equivalent to the consumption of several thousand households. Without load management or buffering, such concentrated demand may cause voltage drops and congestion in local grids. Battery swapping mitigates these challenges by shifting the charging process to off-peak hours and enabling energy storage-based scheduling, thus smoothing the power demand profile and improving grid reliability.

Recent Finland-specific charging demand research further illustrates these challenges in a national context. Empirical analyses based on detailed freight origin-destination data demonstrate that large-scale deployment of MCS for medium- and heavy-duty battery electric trucks may lead to localized megawatt-scale loads at specific nodes of the transport network. Such spatial concentration of demand can create significant pressure on local distribution grids and substations under unfavorable charging synchronization scenarios, thereby highlighting grid capacity and reinforcement as critical constraints for widespread MCS deployment in practice (Samet et al., 2025).

Comparative assessments in Finland (McMonigle et al., 2023; Rashid et al., 2025) suggest that large-scale megawatt charging facilities near logistics hubs could impose grid loads comparable to medium-sized industrial centers, necessitating substation upgrades and new high-voltage connections. In contrast, BSSs, when integrated with local storage or photovoltaic systems, can operate as controlled microgrids, charging batteries during periods of low network load and discharging them during peak demand.

Electric road systems (ERS), on the other hand, distribute electricity dynamically but require continuous medium-voltage supply along the road corridor, which can result in high cumulative transmission demand (Andersson et al., 2025). Hence, while ERS reduces on-site charging peaks, its widespread implementation demands extensive and costly infrastructure.

Simulation-based studies further emphasize the scalability advantage of battery swapping. El Helou et al. (2022) found that if just 11% of heavy-duty vehicles (HDVs) in Texas were to charge simultaneously, transmission-level voltage instability could occur. Battery swapping, by decoupling charging from operation and incorporating local storage, helps avoid such synchronous loading. Similarly, Shirizadeh et al. (2024) estimated that even under full electrification of Europe’s trucks and buses, heavy-duty road transport would account for only about 4% of total final electricity consumption by 2050 indicating that grid strain concerns for managed swapping networks are often overstated.

Additional studies also suggest that well-designed swap stations could enhance grid resilience. When strategically located and coupled with distributed storage, they can act as balancing assets by absorbing surplus renewable energy during production peaks and releasing it during demand surges (Revankar & Kalkhambkar, 2021; Alharbi, 2023; Marchesano et al., 2023).

In summary, compared with megawatt charging and ERSs, battery swapping offers a lower and more predictable grid load profile. Its centralized and schedulable energy management allows integration with renewable sources and buffering systems, providing both operational flexibility and system-level stability features particularly valuable for high-utilization truck fleets across Europe’s increasingly constrained grids.

2.5 Operational Benefits and Performance Characteristics

One of the most frequently cited advantages of battery swapping is its ability to minimise vehicle downtime. Multiple studies report that battery swapping can reduce energy replenishment time to approximately 5-10 minutes, enabling near-continuous vehicle operation and improving fleet productivity (Bhardwaj & Mostofi, 2022; Wang et al., 2025). This rapid turnaround is particularly valuable for HDTs engaged in high-frequency or time-sensitive logistics operations.

Empirical and modelling studies suggest that under certain operating conditions, battery-swappable trucks may outperform both conventional fast-charging battery-electric trucks and even diesel trucks. For example, Zhu et al. (2023) report that battery swapping becomes economically advantageous when vehicle utilisation exceeds 43% and average operating speeds are higher than 32 km/h. These findings highlight the importance of duty cycle characteristics, such as daily mileage and route predictability, in determining the suitability of battery swapping for specific freight applications.

At the system level, battery swapping also enables more flexible energy management by decoupling charging activities from vehicle arrival times. This allows batteries to be charged during off-peak periods or when renewable electricity is abundant, potentially reducing electricity costs and alleviating peak demand pressures. As a result, battery swapping is often positioned as an operationally efficient solution for fleet-based logistics with high utilisation requirements.

2.6 Technical and Institutional Challenges

Despite its operational advantages, battery swapping faces several technical and institutional challenges that may hinder widespread adoption. Battery degradation remains a concern, particularly if charging and thermal management are not adequately controlled. Although advanced battery management systems can mitigate accelerated degradation, improper operational practices may reduce battery lifetime and increase replacement costs (Deng et al., 2023).

Grid impacts are another relevant issue, especially at large-scale swapping stations with high aggregate charging demand. While battery swapping can smooth power demand through controlled charging, inadequate scheduling or insufficient buffering capacity may still impose stress on local electricity networks (Zhu et al., 2022). These challenges underscore the importance of integrating smart charging strategies and local energy storage into swapping station design.

Institutional and regulatory barriers also remain underexplored. In particular, battery swapping introduces complex questions related to insurance, liability, and responsibility for battery performance and failures when battery ownership is separated from vehicle ownership. Existing insurance frameworks are often not well adapted to such arrangements, potentially increasing risk and uncertainty for operators. Although broader discussions on rising insurance and repair costs for electric vehicles exist, targeted research on insurance and liability implications specific to battery-swapping HDTs remains limited, representing a clear gap in the literature.

2.7 Emerging Innovations and Business Models in Battery Swapping

Some high-functioning solutions and business models have entered the field to overcome abiding constraints such as standardization, battery ownership, and capital cost in battery swapping systems. Great example from this changing technological landscape of modular battery architecture includes 'Choco-SEB' design, developed by Contemporary Amperex Technology Co. Limited (CATL), allowing installation or removal of individual battery units like chocolate bars. These modular units comply with around 80% of the world's EV platforms and can be swapped in less than a minute, so dramatic reductions in downtime occur in (CATL, 2022).

In addition, by establishing the Battery-as-a-Service (BaaS) model, ownership responsibility has shifted from users to service providers. In this way, upfront vehicle costs can decrease as much as 50% and the maintenance and replacement management, as well as lifecycle tracking of the battery pack (Shi & Hu, 2022). Some experiments with pilot projects in China have also explored BaaS implementation through subscription-based models and market strategies supported by government incentives (Reuters, 2024).

Moreover, some swapping stations are starting to use advanced digital platforms to enable real-time assessment of battery health and operations; examples include QIJI Cloud (CATL, 2023).

2.8 Technology Readiness Levels (TRL)

Several pilot projects and technical reports have explicitly assessed the TRL of battery swapping systems for HDTs.

In Australia, battery swapping technology by Janus Electric (CleanTechnica, 2025), has attained TRL 9 and complete commercial readiness. The system has been field-tested in commercial fleets, thus completely fulfilling the technical maturity criteria (Piedel et al., 2024).

In China, the rapid deployment of battery swapping into the HDV market took place and 49.5% of electric HDTs in 2022 sold with battery swapping capabilities; therefore, it may have reached TRL 9, a level given when a technology is in very extensive deployment-commercialization stages (Piedel et al., 2024).

European projects such as RouteCharge and E·HAUL (E·HAUL , 2023) remain earlier development phases (TRL 4 to 6), especially for fully automated swapping systems (Speth & Funke, 2021; Piedel et al., 2024).

Reported TRL values are based on project self-assessments and sectoral reports; comparability across regions may vary.

2.9 Current Global Deployment and Regional Trends

Battery swapping for trucks has had different developments in various areas. In China, the two-year pilot program was kicked off by the central government in 2021 in eleven cities, intending to deploy battery-swappable electric vehicles for more than 100,000 vehicles and building 1,000 battery swap stations (Cui et al., 2023). Tangshan, the city in Hebei province that dominates the case, has successfully integrated more than 5,000 swappable trucks with 23 operational stations (Jin, 2023). Major industry players like CATL and Sinopec have also jointly unveiled plans to build over 10,000 battery swap stations nationwide before 2025 (Reuters, 2025). SPIC, which is the largest energy supplier in China, has established what can be termed a comprehensive battery swap infrastructure, including the construction of swap stations, the development of battery logistics systems, and the deployment of digital management platforms to support the operation of heavy-duty electric trucks.

China’s State Power Investment Corporation (SPIC) has made measurable progress in deploying battery-swap infrastructure and swap-enabled commercial vehicles as part of its clean energy transition. According to industry reporting, SPIC has supported tens of thousands of battery-swapping trucks and hundreds of swap and charging stations, with further expansion planned through partnerships and investments in the sector. Over the coming years, planners and industry analysts expect significant scaling of heavy-duty swap infrastructure and vehicle deployments to support broader fleet electrification across China (Joseph, 2023; SASAC, 2025). Recent industry developments further indicate a shift toward standardisation-driven scaling of battery swapping in China. In May 2025, CATL announced a standardised battery swap pack for heavy-duty trucks, aiming to improve interoperability across vehicle manufacturers and reduce deployment barriers for fleet operators. Such standardisation is expected to support large-scale ecosystem development by enabling shared battery assets and lowering investment risk, although detailed assessments of grid-level impacts remain largely addressed in academic modelling studies rather than industry announcements (Zhang, 2025). While interest is growing worldwide, most regions outside China are still in the pilot or pre-commercial stage.

Across Europe, several pilot initiatives are underway. DB Schenker, in collaboration with CATL and Trailer Dynamics, is trialing BSSs for electric semi-trailers (EuropaWire, 2024). In Germany, the E·HAUL project launched the first fully automated battery swap station for heavy trucks, operating on a daily basis (Fraunhofer IVI, 2024; E·HAUL , 2023). In addition, emerging operators such as AkkuSwap in Cottbus are developing fully automated battery swap solutions capable of exchanging e-truck batteries in approximately 6-8 minutes, aiming to reduce downtime and optimise energy costs through flexible grid integration and operational planning (AkkuSwap, 2025). Designwerk Group, a Swiss electromobility company, is also actively involved in the e-truck battery ecosystem with patented battery systems and engagement in industry discussions around battery swapping as a potential game-changing solution for commercial vehicles (Designwerk Group, 2025). In Sweden, the national transport research institute (VTI) has recommended that the government initiate a battery swapping trial program for HDVs (Nåbo et al., 2024). Norway has taken a pragmatic approach through pilot tests with real-world conditions. A 2020 study found that notwithstanding some concerns about battery weight and operational limitations, electric trucks utilizing battery swapping were viable for some use cases.

Sweden stands out in Europe for actively funding pilot projects focused on battery swapping for heavy machinery. The pre-study CONVERGE evolved into CONVERGE II (2024-2027), a project funded with approximately SEK 51 million by the Swedish Energy Agency. This initiative brings together Volvo CE, PEAB, the Swedish Transport Administration, and academic partners to develop system-level solutions for energy distribution and battery swapping in road construction and quarry environments, demonstrating Sweden’s leading role compared to other European countries where the concept remains largely theoretical (Product Development Research Lab, 2024).

In the United States, battery swapping for heavy-duty vehicles is still in the exploration phase, with activities largely limited to early conceptual developments rather than coordinated, large-scale deployment. According to the California State Transportation Agency (CalSTA) (2024), in August 2024 California’s state transport authority organized a policy workshop with Chinese stakeholders and academic researchers to assess implementation opportunities for electric trucks, reflecting early policy-level engagement rather than established practice. Industry initiatives also illustrate the exploratory nature of battery swapping in the U.S.; for example, companies such as Revoy have promoted modular battery swapping concepts that aim to electrify diesel semi-trucks in minutes, although these efforts remain at the demonstration or prototype stage rather than full commercial rollout (Borrás, 2024). In the United States, federal infrastructure planning for electric vehicle charging is primarily shaped by the National Electric Vehicle Infrastructure (NEVI) Formula Program, established under the Bipartisan Infrastructure Law (U.S. Congress, 2021). The NEVI program focuses on the deployment of standardized, corridor-based high-power charging infrastructure and emphasizes open access, interoperability, and minimum power requirements for battery electric vehicles (Federal Highway Administration [FHWA], 2022). While the program is formally technology-neutral, its funding criteria and technical specifications are closely aligned with plug-in charging architectures, implicitly favoring high-power charging solutions over alternative system-level approaches such as battery swapping (FHWA, 2022).

Japan has recently taken an initial step toward deploying battery swapping for commercial electric vehicles on public roads. In August 2024, Mitsubishi Fuso Truck and Bus Corporation (MFTBC), in collaboration with Yamato Transport and Ample, launched Japan’s first public-road battery swapping demonstration for electric trucks in Kyoto (Doll, 2024; News on Japan, 2024, MFTBC, 2024). The pilot project utilises the eCanter electric truck equipped with Ample's modular swappable battery system and a fully automated robotic swapping station, with a targeted battery exchange time of approximately five minutes (Doll, 2024).

The demonstration focuses on assessing operational feasibility, technical performance, and potential business models for battery swapping under real-world urban logistics conditions (Arteaga, 2025). In parallel, Daimler Truck Financial Services Asia introduced the "FUSO Green Lease" scheme to support early commercialisation of swappable-battery electric trucks, indicating growing institutional engagement (Doll, 2024). While Japan remains at an early experimental stage compared to large-scale deployments in China, this initiative positions the country among the limited number of regions actively testing automated battery swapping for heavy-duty vehicles in real traffic environments (News on Japan, 2024).

In addition to these pilot projects, Isuzu Motors Limited has publicly presented a battery-swapping concept for commercial electric vehicles, signalling growing interest among Japanese OEMs in swapping-based solutions as a potential pathway for reducing charging downtime and supporting flexible fleet operations (Isuzu Motors Limited, 2023).

Recent developments show that India is entering an early but increasingly coordinated phase of heavy-duty battery swapping. A key milestone was the launch of India's first battery-swapping-enabled heavy-duty electric truck by Blue Energy Motors (BEM) along the Mumbai-Pune Electric Freight Corridor, confirming the technical feasibility of modular battery replacement for long-haul freight operations (Times of India, 2024; Essar Group, 2025). In parallel, GreenLine Mobility (Essar Group) announced a USD 275 million programme to deploy 10,000 electric and LNG trucks and build a statewide network of battery-swapping and charging facilities, signalling growing industrial commitment to alternative refuelling models in freight transport (GreenLine, 2025). These initiatives are closely aligned with India's Draft Battery Swapping Policy, which emphasises battery interoperability, standardised form factors, and the prioritisation of commercial freight applications as a means of accelerating early market adoption (Bhattacharjee, 2024). Policy discussions highlighted in recent analyses suggest that battery swapping is increasingly viewed as a pragmatic solution to India's operational constraints, particularly high daily mileage, limited depot charging capacity, and the need to minimise vehicle downtime in long-haul freight operations (Bhattacharjee, 2024).

Despite this momentum, India's heavy-duty swapping ecosystem remains at an early stage. Original equipment manufacturer (OEM) participation is limited, interoperability standards are still under development, and most national incentives continue to focus on two- and three-wheelers. As a result, India reflects a growing but still nascent niche in which long-term potential depends on automated station rollout and regulatory harmonisation.

2.10 Conclusion

This chapter provided a comprehensive review of the state of truck electrification, focusing particularly on battery swapping technology. The analysis covered technological foundations, competing alternatives, infrastructure and operational challenges, and region-specific deployment examples. Battery swapping demonstrates substantial advantages in minimizing downtime and decoupling charging from grid stress, especially in high-utilization logistics applications, however, challenges in standardization, capital investment, policy support, and long-term economic viability still remain.

China is the only country leading with large-scale deployments and integrated infrastructure, while other regions are in early-stage experimentation or limited pilot testing.

Despite the fast-growing body of research, numerous gaps still exist. Among the most important ones are in policy harmonization, insurance liability frameworks, and cross-border interoperability. These areas require further attention in future studies to enable scalable, sustainable adoption of battery swapping systems in heavy-duty freight transport.

3 METHODOLOGY

This chapter presents the methodological approach used to address the six research questions of this thesis. Battery swapping for HDTs is an emerging socio-technical field involving engineering, logistics, economics, energy systems, and policy, so a single method could not sufficiently capture the complexity of the topic. Therefore, a mixed-methods, pragmatist, and abductive research design were adopted. The structure of this chapter follows the logic of the Research Onion (Saunders et al., 2019), progressing from philosophical stance to data collection and analysis techniques.

3.1 Research Design

3.1.1 Philosophical stance: Pragmatism

The study adopts a pragmatist philosophy, which prioritises methodological flexibility and seeks practical, evidence-based solutions rather than adherence to a single paradigm. This stance is suitable for analysing battery swapping, where technical, economic, environmental, and policy considerations intersect. Pragmatism enables the combination of qualitative evidence (expert interviews, thematic insights) and quantitative elements (cost figures, grid indicators, infrastructure data) to answer the research questions.

3.1.2 Reasoning logic

The study follows an abductive reasoning logic (Timmermans & Tavory, 2012), which allows iterative movement between theory and empirical observations. The Multi-Level Perspective (MLP) served as the initial conceptual lens for positioning battery swapping within wider socio-technical transitions. Rather than treating MLP as a fixed hypothesis-testing framework, the abductive approach allowed the theory to evolve in response to empirical data gathered from interviews, case studies, and grey literature.

Four initial assumptions derived from MLP guided the research:

1. Battery swapping currently functions as a niche innovation within heavy-duty transport.
2. The dominant diesel and plug-in charging regime imposes infrastructural and institutional lock-ins.
3. Landscape pressures such as EU decarbonisation targets and AFIR regulations create opportunities for alternative charging paradigms.
4. The evolution of battery swapping is shaped by niche-regime interactions and actor networks across technical, economic, and policy domains.

Multiple empirical findings from interviews and global case studies required updating the classical MLP assumptions and they were continually revisited as new evidence emerged. For example, battery swapping exhibited accelerated niche industrialisation (China, Australia), regime-enabled adoption pathways (Europe), mixed landscape pressures (AFIR), and the emergence of powerful non-traditional actors (CATL, utilities), none of which align neatly with conventional MLP transition patterns.

3.1.3 Analytical Framework: Multi-Level Perspective (MLP)

MLP was adopted as the guiding analytical lens to understand how battery swapping fits within the broader socio-technical transition of HDT electrification. The framework conceptualises transitions as interactions between niche innovations, the dominant socio-technical regime, and wider landscape pressures (Geels, 2002; Geels & Schot, 2007). The Multi-Level Perspective (MLP) is used in this study mainly as an analytical framework to organise and interpret evidence on niche–regime interactions, rather than as a theory for predicting transitions. Its main limitations—such as limited ability to capture rapid changes, geopolitical shocks, and firm-level strategies—are recognised. To address these limitations, the analysis is supported by empirical evidence from a systematic literature review, grey literature, and expert interviews. The focus is therefore placed on observable coordination mechanisms, including standardisation processes, business models, and policy alignment, instead of assuming simple or linear transition pathways.

In this thesis, battery swapping is treated as a niche innovation interacting with both the entrenched diesel-based freight regime and the emerging fast-charging regime. The use of MLP is aligned with the abductive research logic of this study: instead of applying the framework in a purely deductive manner, preliminary assumptions derived from classical MLP literature were iteratively refined as empirical findings emerged from interviews, grey literature, and recent analyses of heavy-duty electrification dynamics.

Empirical evidence revealed dynamics that diverge from conventional linear MLP expectations. Interview findings highlighted accelerated niche industrialisation in China and Australia, partial regime accommodation in Europe, and strong landscape pressures through EU-level policies such as AFIR. These hybrid and non-linear patterns reflect emerging scholarship that emphasises the limitations of traditional regime-shift models in fast-evolving electrification domains (Köhler et al., 2019).

Accordingly, MLP is used in this study as a flexible and diagnostic analytical tool, aimed at interpreting niche-regime interactions, policy leverage points, and actor dynamics rather than as a deterministic transition model. The framework also supports triangulation with the systematic literature review (SLR) and informs the structuring of the empirical findings in Chapters 4 and 5.

Using MLP together with TRL allowed the study to analyse both the technological readiness of battery swapping and its systemic position within the transition in a complementary manner. Furthermore, MLP was chosen because it is particularly suitable for analysing technologies that evolve through interactions between policy, markets, infrastructure, industry actors, and user behaviour, characteristics that make it more appropriate for a complex system such as battery swapping compared to purely technological or economic models.

3.1.4 Research strategy: Mixed-methods design

A mixed-methods strategy (Creswell & Plano Clark, 2018) was selected to accommodate the diversity of the research questions, which range from descriptive (RQ1), to analytical (RQ4-RQ5), to comparative (RQ6). Mixed-methods strengthen validity through methodological triangulation, ensuring that findings are not dependent on a single source or type of evidence.

The research design integrates:

- Systematic Literature Review (SLR) to establish the conceptual and empirical foundation (RQ1-RQ6)
- Grey literature review to capture real-time technological and commercial developments (RQ1-RQ6)
- Case studies to contextualize deployment conditions (RQ1-RQ4)
- Semi-structured expert interviews to gather practitioner insights (RQ1-RQ6)
- Grid impact analysis to examine electricity system implications (RQ5)
- Multi-criteria decision analysis (MCDA) to compare technologies (RQ6)

Together, these methods form a coherent framework for analysing both the technical feasibility and systemic implications of battery swapping.

3.1.5 Time horizon: Cross-sectional with longitudinal evidence

The primary research design is cross-sectional, with interviews conducted between July and September 2025. Longitudinal evidence from 2020-2025 (deployment trends, policy evolution, TRL changes) was incorporated through academic and grey literature, ensuring temporal depth in the assessment of technology and policy developments.

3.1.6 Analytical frameworks and modelling

The study employed a combination of qualitative and quantitative analytical frameworks:

- Structured SLR protocol (Kitchenham et al., 2009)
- Thematic coding of interviews (Braun & Clarke, 2006)
- Socio-technical interpretation through the MLP framework
- Indicative grid impact assessment using secondary quantitative data (charging loads, peak demand, load shifting)

- MCDA to evaluate comparative performance of battery swapping, plug-in FC, and hydrogen fuel cells

Quantitative elements were used to contextualize rather than replace qualitative findings, ensuring alignment with the pragmatist and abductive principles of the study.

3.2 Data Collection

The study utilized two complementary data sources: secondary data (SLR, grey literature and documented case evidence) and primary data (expert interviews).

3.2.1 Secondary Data

Secondary data includes a systematic literature review (SLR), a structured grey literature review, and documented case evidence from real-world deployments. The core analytical focus of the literature review is on studies published between 2020 and 2025, reflecting the period during which battery swapping for heavy-duty trucks transitioned from conceptual and pilot-stage discussions toward early commercial deployment and policy integration. Earlier sources are selectively included where necessary to establish historical context and foundational concepts. Together, these sources form the foundation for all six research questions.

Searches were conducted in Scopus, Web of Science, and ScienceDirect, supplemented by targeted searches for industry reports, technical documentation, and regulatory material. The initial search returned 951 records.To ensure methodological rigour, the following screening process was applied:

(1) Deduplication, removing overlapping items across databases.

(2) Title and abstract screening, using predefined inclusion and exclusion criteria.

(3) Full-text assessment for studies meeting screening criteria.

(4) Snowballing, adding relevant sources cited by included papers.

After deduplication, title/abstract screening, full-text assessment, and snowballing, 61 academic studies were included in the final evidence set. In addition to the SLR results, a total of 164 academic and grey literature sources were used throughout the thesis, including industry reports, regulatory documents, technology whitepapers, and real-world case evidence. This broader integration ensured comprehensive coverage of both scholarly knowledge and rapidly evolving industry developments.

3.2.1.1 Systematic Literature Review (SLR)

The literature review followed established systematic review principles outlined by Kitchenham et al. (2009) and adopted a rapid, structured review approach in line with guidance on systematic and semi-systematic reviews for management and engineering research (Snyder, 2019). Inclusion criteria focused on publications addressing:

- battery swapping systems
- heavy-duty electric trucks
- charging infrastructure
- costs and performance
- grid integration
- hydrogen or FC alternatives

The included studies were categorised into six thematic clusters aligned with RQ1-RQ6. These categories guided further synthesis and the design of interviews, grid-impact assumptions, and MCDA criteria.

3.2.2 Grey Literature Review

The rapid evolution of battery swapping in heavy-duty applications means that much of the most recent and practically relevant information appears in grey literature rather than academic journals. Therefore, a structured grey literature review was conducted in parallel with the SLR to capture:

- deployment statistics,
- TRLs,
- station design and operational data,
- cost structures,
- business models and interoperability developments,
- policy directions and industrial strategies.

Grey literature was evaluated using four quality criteria:

- Recency: Documents published between 2015 and 2025 to ensure technological relevance.
- Credibility: Material produced by recognised organisations such as industry leaders (e.g., CATL, SANY), public authorities, utilities, research institutes, or international organisations (e.g., ICCT).
- Relevance: Direct linkage to battery swapping for HDVs, with emphasis on technical specifications, deployment data, cost information, and grid-related considerations.
- Verifiability: Data traceable through documented methodology, official reporting, or publicly available technical metrics.

Typical sources included major OEM publications (e.g., CATL, SANY), utility publications (e.g., Chinese State Grid, Nordic utilities), government reports (e.g., ICCT, European Commission), and public documentation of pilot projects (e.g., Janus Electric in Australia, mining/off-road deployments in the Nordics and China).

Grey literature was analysed using the same thematic structure as the SLR. Integrating academic and grey sources reduced publication bias and strengthened the empirical grounding for assessing TRL, costs, interoperability, and infrastructure implications.

3.2.3 Primary Data: Expert Interviews

Primary data for this research were collected through semi-structured expert interviews, designed to complement the secondary data and provide practitioner-level insights into the technological, economic, and policy dimensions of battery swapping for HDTs. Interviews were particularly important because commercial battery swapping remains an emerging field in which industry actors and policymakers often possess the most up-to-date knowledge, exceeding what is documented in academic publications.

Semi-structured interviews offer both comparability across participants (through shared thematic questions) and flexibility to capture unexpected insights (Kvale & Brinkmann, 2009). This approach ensured alignment with the six research questions while allowing experts to elaborate on practical experiences, strategic considerations, and region-specific challenges. Interviews were used to complement documentary evidence, particularly for regions where formal policy frameworks are still emerging.

Purposive sampling was used to identify individuals with direct professional experience in truck electrification, battery swapping systems, charging infrastructure, grid operations, or policy design. Eleven experts agreed to participate. Eleven interviews were conducted synchronously via Microsoft Teams (30-85 minutes) and, with prior consent, were audio-recorded, transcribed verbatim, anonymised, and stored securely in compliance with GDPR requirements. One expert provided written asynchronous responses via LinkedIn, which were anonymised and archived using the same data-protection procedures (Appendix A, Table 6).

While the interview sample is small by design (n=11) and includes several Nordic perspectives, interviews are not used to estimate population parameters; they are used to elicit mechanisms and decision logics, which are then triangulated against SLR and grey literature evidence. Weighting vectors are drawn from four role-representative informants to avoid over-representing the larger academic subgroup and to preserve stakeholder balance in the MCDA aggregation.

3.2.3.1 Sampling Strategy

The sampling aimed to ensure representation across key segments of the heavy-duty transport ecosystem:

1. Academia and Research Institutes: perspectives on technology readiness, transition pathways, and system-level impacts.

2. Industry and OEMs: insights into vehicle design, interoperability, business models, and engineering constraints.
3. Fleet Operators and Users: operational perspectives on charging downtime, logistics integration, and cost considerations.
4. Policy and Public Authorities: understanding of regulatory frameworks, incentives, and infrastructure planning. Anonymised roles, areas of expertise, and interview details are summarised in Appendix A.

3.2.3.2 Data Analysis

Interview transcripts were analysed using inductive thematic analysis (Braun & Clarke, 2006) (Appendix A, Section A4):

1. Open coding: identifying recurring concepts, concerns, and insights mentioned by the participants.
2. Thematic clustering: grouping codes into higher-order categories aligned with the research questions (e.g., “Interoperability challenges”, “Grid constraints”, “Fleet economics”).
3. Interpretive analysis: connecting emergent themes with insights from the SLR and interpreting findings through the MLP framework.

This approach ensures transparency, replicability, and strong integration of practitioner perspectives into the socio-technical analysis. The interpretive step provides a direct bridge between the empirical material and the MLP-based discussion that follows in Chapters 4 and 5.

3.2.3.3 Ethical Considerations

Interviews followed ethical research standards: participation was voluntary, experts were informed of withdrawal rights, confidentiality was ensured through anonymisation, and data were stored securely. These measures preserve the reliability and credibility of the qualitative dataset.

3.3 Multi-Criteria Decision Analysis

To address RQ6, “How does battery swapping compare with other electric and hydrogen fuel cell alternatives?”, the study applies a Multi-Criteria Decision Analysis (MCDA). MCDA is widely used in energy and transport research to evaluate technologies that differ along multiple dimensions and where trade-offs cannot be expressed through a single metric.

MCDA enables the systematic comparison of battery swapping (BSS), MCS), and hydrogen fuel cell (H_2-FC) systems by integrating evidence from literature, grey sources, interviews, and grid considerations. The objective is not to produce a deterministic ranking, but rather to generate structured, transparent comparative insights (Appendix B).

3.3.1 Data Sources and Credibility Hierarchy

The scoring of technologies was informed by a structured synthesis of diverse evidence types (Appendix B, section B2). Peer-reviewed academic literature provided the most reliable foundation due to its methodological transparency and independent evaluation. Industry and utility reports contributed up-to-date technical and operational data, although these were treated as medium-reliability sources, as they may reflect commercial or organisational priorities. Expert interviews offered contextual and practice-based insights into engineering constraints, operational realities, and policy considerations that are not yet fully reflected in published studies.

To ensure consistency and reliability in interpreting evidence, a credibility hierarchy was applied. Peer-reviewed publications were prioritised whenever available; industry, utility and governmental reports were used to complement empirical gaps; and interview evidence was incorporated to validate findings and capture practitioner perspectives. Across all source types, emphasis was placed on recent publications and those with direct relevance to the European HDT context. This ensured that the assessment reflects realistic technological maturity, regulatory conditions and deployment constraints, thereby reducing the risk of over-reliance on speculative or single-sourced claims and strengthening the robustness of the MCDA results.

3.3.2 Aggregation and Analysis

Weighted scores were aggregated using a linear additive model, in which each technology’s final performance value results from the combination of its criterion scores and the corresponding weight sets (Appendix B). This modelling approach is widely used in early-stage technology assessment because it provides a transparent structure for comparing heterogeneous attributes, technical, economic, environmental and infrastructural, without requiring precise quantitative predictions. The model accommodates both expert-derived weights and the thematic weighting scenarios developed earlier, allowing the evaluation to reflect multiple decision priorities. The full set of MCDA outcomes, including scenario-specific results and sensitivity analysis, is presented in Chapter 4.

3.3.3 Limitations

The MCDA results should be interpreted as indicative comparative insights rather than definitive rankings. The analysis relies on heterogeneous data drawn from different geographic regions, deployment scales and maturity levels, which may influence the comparability of performance indicators. Although the expert panel was intentionally designed to represent distinct stakeholder groups, its small size introduces inherent limits to the breadth of perspectives included. The linear additive model also simplifies complex interactions between cost, infrastructure constraints, regulatory factors and operational behaviour. Despite these limitations, the triangulation of academic literature, grey sources, expert interviews and scenario-based weighting substantially enhances the robustness and credibility of the assessment.

3.4 Analytical Methods

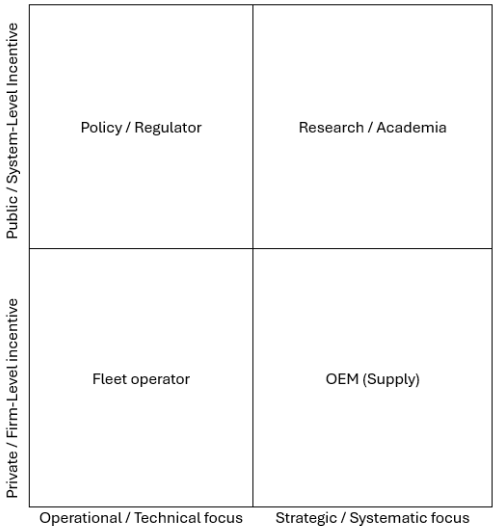
3.4.1 Semi-quantitative scoring based on literature synthesis

A semi-quantitative scoring method was used to allow comparison between technologies that differ in data type, scale and availability. By normalising heterogeneous indicators (e.g., minutes, €, gCO_2/km, MW), the method ensures consistent evaluation across the seven MCDA criteria. This approach, widely applied in energy MCDA and LCA studies, synthesised peer-reviewed findings, technical reports and operational evidence to provide a structured assessment of BSS, MCS and H_2-FC performance (Appendix B, Section B1).

3.4.2 Expert-based weighting

Expert involvement in the weighting process was not intended to produce a statistically representative sample but to ensure the inclusion of the key perspectives relevant to the future deployment of battery swapping for HDTs. In MCDA practice, the value of expert elicitation lies in the diversity and depth of knowledge that a small, carefully selected panel can offer, rather than in large sample sizes (Keeney & von Winterfeldt, 1991). For this reason, four experts were purposefully selected from the wider interview pool, each representing a distinct stakeholder group: (1) policy and regulatory authorities, (2) vehicle manufacturers (OEMs), (3) fleet operators, and (4) research and analysis organizations. This ensured balanced representation of regulatory, industrial, operational and analytical viewpoints and prevented dominance by any particular actor category. Figure 1 illustrates the conceptual framework used to select experts for MCDA weighting.

Figure 1. *Decision-Logic Framework for Expert Selection in MCDA Weighting*



Experts were chosen to represent four archetypal decision-making logics in heavy-duty truck electrification, regulatory, supply-side, demand-side, and analytical across public/private and operational/strategic dimensions. This design aims to ensure perspective saturation rather than statistical representativeness. By covering these four institutional logics, the weighting process captures the fundamental trade-offs inherent in the socio-technical system, rather than reflecting the preferences of a random or homogeneous sample.

While the selected experts are based in Europe and China, their professional roles are global in scope. The fleet operator manages transnational logistics operations; the OEM representative is involved in global vehicle platform and technology strategy; the policy expert contributes to regulatory frameworks such as AFIR; and the academic expert analyses battery swapping developments across multiple regions. As a result, the elicited weights reflect institutional decision logics embedded in the global HDT sector rather than region-specific preferences.

To further strengthen methodological robustness and reduce dependence on the judgments of this small expert panel, several complementary weighting strategies were applied. Three thematic scenarios were constructed to reflect alternative decision priorities: an economics-oriented scenario emphasising cost and utilisation, a policy and grid-oriented scenario highlighting regulatory compatibility and grid integration, and an environment-oriented scenario focusing on lifecycle sustainability. In addition, an equal-weight scenario was included as a neutral benchmark, and an aggregate-mean scenario was used to approximate the outcome of a larger and more heterogeneous expert group. Sensitivity analysis was then performed to assess the stability of technology rankings across these alternative weighting configurations (Appendix B).

The consistency of results across multiple expert-based and scenario-based weighting schemes demonstrates that the MCDA outcomes are not overly dependent on the specific judgments of the four selected experts. Instead, the combination of deliberately structured expert selection, scenario testing, and sensitivity analysis provides a transparent and robust foundation for the comparative assessment of battery swapping, megawatt charging, and hydrogen-based pathways.

3.4.3 Conceptual Load Analysis

To address RQ5, a dedicated analysis was conducted to examine the implications of large-scale deployment of BSSs on electricity grids. This component of the study relied on secondary quantitative data obtained from published grid modelling studies, technical reports, and national energy scenarios (Appendix D) (e.g. ENTSO-E, n.d; State Grid China, 2024).

The analysis focused on three core parameters commonly used in EV-grid integration research:

1. **Peak power demand:** the maximum instantaneous load generated by simultaneous charging of multiple swap batteries.
2. **Load-shifting and off-peak utilization:** the extent to which BSS can act as controllable demand, charging batteries during low-demand periods; and

3. **Grid infrastructure requirements:** indicative estimation of connection capacity, transformer sizing, and reinforcement costs per station.

For each parameter, indicative ranges were derived from existing simulation models and technical benchmarks for fast-charging stations and energy storage systems. The resulting data were used to develop a comparative understanding of the grid impact profiles of BSS relative to megawatt charging and hydrogen refuelling alternatives.

No new grid model was constructed; instead, the analysis synthesized existing evidence to contextualize grid-related findings from the interviews and literature. This approach aligns with exploratory research design principles, providing a grounded but non-simulated understanding of grid interaction patterns under realistic deployment assumptions.

However, several limitations must be acknowledged. The assessment relies entirely on secondary grid-modelling data, meaning that results are influenced by the assumptions and boundary conditions of the original studies. The absence of a new simulation model also prevents the analysis from capturing local network conditions such as feeder constraints, spatial variations, or renewable generation fluctuations. Furthermore, the indicative ranges extracted from literature represent heterogeneous system contexts, limiting direct comparability across technologies and regions. The analysis additionally assumes idealised operational strategies such as optimised off-peak charging which may not fully reflect real operator behaviour. Consequently, the grid impact findings should be interpreted as contextual and indicative rather than precise engineering estimates.

Comparing megawatt charging stations and battery swapping stations (BSS) highlights a fundamental difference in their interaction with the electricity grid. While MCS relies on very high instantaneous power demand during charging events, BSS decouples vehicle operation from battery charging by charging batteries gradually over time and delivering energy to vehicles on demand. This analysis estimates the required stationary battery capacity and demonstrates how intermediate storage can significantly reduce peak grid load. The numerical results are illustrative, whereas the key contribution lies in demonstrating the underlying system-level principle of peak-load smoothing.

3.5 Summary of the Methodological Framework

This chapter presented the methodological framework adopted to investigate the six research questions of the study. A pragmatic and abductive approach guided the use of mixed methods combining systematic and grey literature reviews, expert interviews, and analytical evaluations. The integrated framework comprising qualitative insights and semi-quantitative analyses ensured both empirical grounding and analytical rigour. The interpretive use of the MLP framework provides a unifying lens for linking empirical findings to broader socio-technical transition dynamics. Together, these methods provide a coherent basis for the findings discussed in Chapter 4 and their interpretation in Chapter 5.

4 FINDINGS

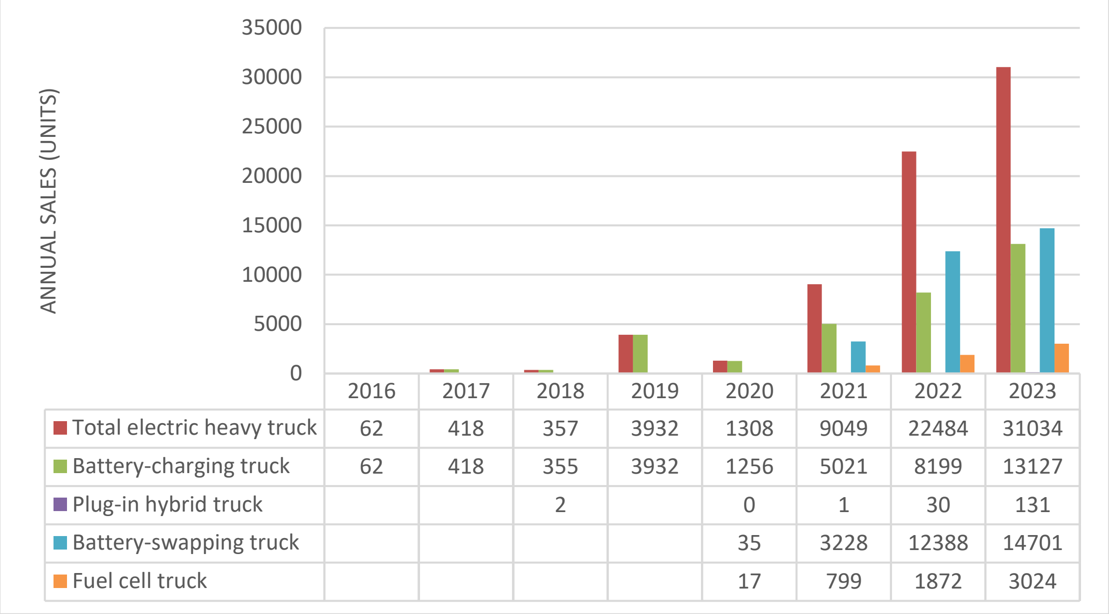
This chapter presents the empirical findings of the study by integrating evidence from the SLR, grey literature, expert interviews, the grid-impact model, and the MCDA. Each subsection directly addresses one of the six research questions and follows the methodological logic introduced in Chapter 3. The structure ensures full traceability between data sources, analytical methods, and resulting insights. The chapter concludes with a synthesis identifying cross-cutting patterns and their implications for the wider electrification landscape.

4.1 Current Status and Role of Battery Swapping in HDT Electrification

Battery swapping for HDTs has emerged as a technologically mature but institutionally uneven solution whose global deployment is characterized by strong regional divergence. Findings from the SLR and coded interviews reveal that while the core battery swapping technologies are technically mature and fully proven, scaling remains more dependent on industrial coordination, standardisation, and regulatory alignment than on engineering limitations.

4.1.1 China: The Only Commercial-Scale Deployment

China stands out as the only country where heavy-duty battery swapping operates at genuine commercial scale. In 2023 alone, approximately 14,700 battery-swapping heavy-duty electric trucks were sold in China, primarily for deployment in port logistics, mining transport, and regional freight corridors (Li et al., 2024). Figure 1 summarizes the empirical sales evidence used in this study to assess the current commercial status of battery swapping in China.



	2016	2017	2018	2019	2020	2021	2022	2023
🟥 Total electric heavy truck	62	418	357	3932	1308	9049	22484	31034
🟩 Battery-charging truck	62	418	355	3932	1256	5021	8199	13127
🟪 Plug-in hybrid truck			2		0	1	30	131
🟦 Battery-swapping truck					35	3228	12388	14701
🟧 Fuel cell truck					17	799	1872	3024

Figure 2. *Annual sales of new energy HDTs in China by technology pathway (2016-2023)*

Source: Adapted from Li et al. (2024)

Interviewees with first-hand experience described Chinese swapping stations as functioning similarly to conventional refueling hubs: "*highly automated, reliable, and embedded within vertically coordinated industrial ecosystems*". National policies mandating standardized battery interfaces, combined with strong organizational alignment between OEMs, CATL, State Grid, and station operators such as Aulton, have created a uniquely coherent environment that enables scaling. The Battery-as-a-Service (BaaS) model has further accelerated adoption by lowering upfront vehicle costs and centralizing battery health management. The literature confirms that early standardization and vertically integrated actor coordination are decisive factors in China's market success. This interpretation is supported by consistent patterns observed across multiple empirical studies and corroborated by interviewees with direct operational experience in China.

4.1.2 Europe: Technically Feasible but Structurally Constrained

Europe exhibits strong technological potential but faces persistent institutional barriers that hinder large-scale deployment. Interview evidence indicates that European OEMs deliberately maintain proprietary battery architecture because they regard the battery pack as a core competitive asset and a strategic technological domain. As one expert emphasized, "*they don't want to lose the battery from their business*", highlighting a deliberate effort to preserve technological ownership and market control.

This strategic protectionism prevents the emergence of shared interfaces and renders cross-OEM interoperability structurally infeasible. Several interviewees further noted that this resistance is reinforced by competitive considerations, as "*European manufacturers know that the Chinese* *actors are so much ahead of them*", and therefore perceive standardization as a potential loss of market position. The literature supports this interpretation, consistently showing that European battery systems remain highly diversified and lack the unified standards required for cross-OEM battery swapping.

In addition to OEM-level constraints, structural characteristics of the European freight system further limit the viability of battery swapping. Freight flows in Europe are more heterogeneous than those in China, reducing the utilization levels necessary for swap stations to achieve economic viability. At the policy level, frameworks such as AFIR prioritize megawatt charging, directing regulatory attention and investment toward plug-in solutions rather than battery swapping.

As a result, battery swapping in Europe remains confined to early-stage pilots, including initiatives by E·HAUL, Designwerk, and AkkuSwap. Interview evidence confirms the lack of continuity and scaling beyond the pilot phase. One expert noted that "*I had a pilot in Sweden that didn't work out because they didn't want to participate anymore*", while another explained that "*transporters don't want to try it… they can't start buying trucks from China to experiment*". Taken together, these interview statements point to an institutional rather than technical constraint, where proprietary OEM strategies and competitive positioning inhibit interoperability and large-scale diffusion. These observations indicate that European battery-swapping initiatives remain fragmented, short-lived, and unable to transition beyond prototype or demonstration stages.

4.1.3 United States, India, Australia, and Japan

Outside China and Europe, battery swapping for HDTs remains an early-stage niche shaped not by technical immaturity but by incomplete ecosystem formation and weak cross-industry coordination. Evidence from the SLR and expert interviews shows that these regions exhibit promising operational contexts but lack the regime-level alignment required for widespread scaling.

Across all four regions, interviewees consistently emphasised that the primary constraint in heavy-duty electrification is vehicle uptime rather than battery capacity. As one expert noted, "charging is the bottleneck, not electrification." In high-utilisation logistics environments such as depot-based operations, mining, regional freight corridors, and multi-shift fleet cycles battery swapping directly addresses this barrier by eliminating charging dwell time. The ability to decouple energy replenishment from truck operation allows stations to charge batteries slowly and predictably, reducing peak loads and thermal stress. Empirical studies confirm that controlled off-board charging improves both grid stability and battery longevity, reinforcing the operational advantages identified by practitioners.

Economic and organisational factors further shape the niche character of swapping in these regions. Interviewees repeatedly identified Battery-as-a-Service (BaaS) as essential for adoption outside China, as it reduces upfront vehicle cost and shifts degradation risk from fleets to infrastructure providers. However, they also highlighted that BaaS introduces financial exposure for operators, who must invest in spare battery inventory and automated infrastructure. As several experts stressed, swapping becomes economically viable only when utilisation rates are high and supported by long-term fleet commitments conditions that remain uncommon in emerging markets where OEM participation is limited.

Interpreted through the MLP, developments in the United States, India, Australia, and Japan reflect the behavior of niche innovations operating within entrenched socio-technical regimes. Regime structures, including diesel-based logistics configurations, proprietary OEM battery architectures, and policy frameworks favoring CCS/MCS charging act as powerful lock-ins that restrict the expansion of swapping. Landscape pressures such as climate targets, rising energy prices, and concerns over grid congestion offer potential windows of opportunity. Yet, without institutional mechanisms for standardization and coordinated investment, these pressures alone do not lead to regime reconfiguration.

Overall, the findings demonstrate that battery swapping outside China functions as a context-dependent, operationally advantageous but institutionally constrained niche. It performs best in predictable, intensive logistics settings, yet remains unlikely to achieve broader penetration without substantial advances in OEM cooperation, regulatory alignment, and ecosystem coordination. In short, the current role of battery swapping in these regions is defined less by technological limitations than by the degree of socio-technical alignment necessary for diffusion.

4.2 Available Technologies for HDTs

A distinct category of battery swapping has emerged in off-road and industrial environments such as mining, quarrying, and construction. In these contexts, battery exchange is typically based on containerized or top-lifted battery modules that are handled using existing heavy equipment, such as cranes or loaders, rather than dedicated automated swapping stations (Epiroc, n.d.; Sandvik, 2021). Documented industrial deployments indicate that leveraging on-site machinery enables cost-effective and operationally robust operation under controlled conditions, supporting high vehicle utilization and short turnaround times. A concrete example is the ongoing trial of battery-swap electric haul trucks at the Oyu Tolgoi mine, where battery swapping is used to minimise downtime and enable continuous operation in a mining environment (Rio Tinto & SPIC Qiyuan, 2025).

However, these systems are inherently site-specific and rely on non-standardised handling arrangements that are incompatible with road-legal HDT architectures. Consequently, their relevance for mainstream on-road battery swapping remains limited. This limitation is also highlighted in system-level feasibility assessments, which explicitly conclude that off-road battery swapping solutions cannot be directly transferred to road-legal HDTs due to regulatory requirements, dimensional constraints, and the absence of harmonized technical standards (Nåbo et al., 2024).

4.2.1 China’s Dominant and Fully Mature Architecture

China’s architecture was repeatedly described by experts as a “*de facto standard*” for heavy-duty battery swapping. The dominant configuration relies on large, standardized battery packs mounted behind the cab, which are removed vertically or via automated underbody gantry systems. Market data indicate that the most common battery capacities deployed in China in 2024 were 282 kWh, 350 kWh, and 423 kWh, reflecting a trade-off between battery cost and operational efficiency (Mao & Rodríguez, 2025). Interviewees with direct operational experience further reported that these systems are fully automated, require minimal manual intervention, and consistently achieve three- to five-minute exchange times.

4.2.2 Europe’s Fragmented and Prototype-Driven Approaches

In Europe, development is characterized by multiple incompatible design philosophies and a complete absence of cross-OEM standardization (Nåbo et al., 2024; Naumanen et al., 2019). Projects such as E·HAUL, AkkuSwap, and Designwerk have produced advanced prototypes including side-loading trays, chassis-integrated multi-pack systems, and modular retrofit platforms. While these designs attempt to minimize modifications to OEM chassis structures, expert interviews repeatedly highlighted the mechanical and electrical complexity of achieving safe and repeatable swaps. As one engineer explained, “*you have to handle over 1.5 tons really precisely… there’s a lot of mechanical effort in it*”. He also noted that misalignment or uneven voltages across parallel packs can “*get a lot of vehicle problems*” during swapping. Another expert emphasized that “*some vehicle architectures are not capable of being upgraded for swapping*”, reinforcing the structural incompatibility of several European OEM designs.

4.2.3 Off-Road and Industrial Containerized Systems

A third category of battery swapping has emerged in off-road environments such as mining, quarrying, and construction, where battery exchange relies on containerized or top-lifted battery modules handled using existing heavy equipment such as cranes or loaders rather than dedicated automated swapping stations. Industrial case descriptions indicate that leveraging on-site machinery enables cost-effective and operationally robust solutions in controlled environments, supporting high utilization rates and rapid turnaround times. However, because these systems depend on non-standardized handling arrangements and are designed for site-specific, non-road-legal vehicles, they are unlikely to influence mainstream on-road battery swapping development. This limitation is also highlighted in system-level feasibility assessments, which explicitly note that off-road battery swapping solutions cannot be directly transferred to road-legal HDT architectures due to regulatory, dimensional, and standardization constraints (Nåbo et al., 2024).

Cross-Cutting Technical Subsystems

Despite architectural diversity, several enabling subsystems were consistently identified across all battery-swapping configurations. Interviewees repeatedly emphasized the critical importance of high-precision mechanical alignment, explaining that reliable swapping depends on exact positioning of heavy-duty battery packs at the vehicle interface. Given the large mass of truck batteries, even small positioning errors were described as capable of preventing successful mechanical engagement or causing downstream operational issues during repeated swap cycles (Interviews A-E, 2024).

Thermal interfaces were highlighted as another central subsystem. Experts noted that battery cooling design strongly constrains pack geometry and integration, making reliable thermal coupling between the battery and the vehicle particularly challenging in interchangeable systems. Several interviewees argued that battery performance, durability, and safety in HDTs are fundamentally shaped by cooling architectures, and that decoupling the battery from vehicle-specific thermal design introduces additional engineering complexity in swapping-based concepts (Interviews B-E, 2024).

Digital interoperability was further described as a persistent bottleneck, especially in European contexts. Interviewees pointed to difficulties in exchanging battery state-of-health (SoH) data, firmware compatibility information, charging histories, and diagnostic signals between trucks and swapping stations in the absence of harmonized standards across OEMs. These challenges were repeatedly characterized as more critical to system reliability than the robotic handling of battery packs itself. System-level assessments similarly conclude that interface standardisation, including BMS communication and thermal integration, represents a key technical barrier to scalable deployment of battery swapping for HDTs (Nåbo et al., 2024).

4.2.4 Interpretation Through the MLP

Viewed through the MLP, these technological pathways reflect niche solutions shaped by regime conditions. In China, strong alignment across the regime, uniform battery platforms, national standards, and vertically integrated industrial coordination allowed one dominant design to scale to TRL 9. In Europe, competing OEM architectures, proprietary design strategies, and entrenched industry norms maintain a regime environment that resists the emergence of a unified niche. Off-road containerized systems represent isolated niches that thrive where regime constraints are weak or irrelevant. As interviewees noted, several architectures “are not capable of being upgraded for swapping,” and OEMs maintain distinct mechanical and electrical platforms that make cross-OEM compatibility technically difficult.

4.2.5 Synthesis

Overall, while the mechanical feasibility of heavy-duty battery swapping is well established, the scalability of each architecture depends heavily on the socio-technical context in which it is embedded. China’s automated behind-the-cab system remains the only globally mature pathway due to strong standardization and industrial alignment. European systems remain prototype-based and limited by institutional fragmentation rather than engineering shortcomings. Off-road systems demonstrate conceptual flexibility but are unlikely to shape long-haul road transport.

Long-term viability will hinge on harmonized interfaces, standardized thermal and digital protocols, and operational contexts with sufficiently high utilization to justify the capital investment required for automated swapping. One expert stated that “every OEM is pursuing its own battery strategy… there is no interest in a standard battery”, and that major differences in “mechanical dimensions, voltage levels and cell chemistry” further complicate interoperability.

4.3 Technology Readiness Levels (TRLs) Across Regions

The TRL levels reported in this section are based on a triangulated assessment combining evidence from expert interviews, documented pilot and deployment cases, and relevant academic and grey literature. The final TRL assignments therefore reflect an integrative evaluation rather than a single-source judgement. The analysis of Technology Readiness Levels (TRLs) reveals a highly uneven global maturity pattern for heavy-duty battery swapping, shaped far more by institutional alignment and standardization than by engineering capability. Evidence from the literature and interviews shows that the core technologies required for automated battery swapping, robotics, mechanical alignment, thermal coupling, high-voltage interfaces, and BMS communication are already technically viable across regions. However, only China has been able to translate this technical viability into full commercial deployment. In contrast, Europe, the Nordics, and the United States remain in early prototyping stages, with progress constrained primarily by fragmented OEM architectures and the absence of coordinated regulatory frameworks.

Interviewees with direct operational experience in China consistently stated that “the technology is completely ripe,” emphasizing that fully automated swapping stations involving robotic lifting, precise docking, and real-time State of Health (SoH) synchronization operate on a daily basis in ports, mining corridors, and regional freight hubs. These observations align with documented evidence showing that China’s heavy-duty swapping ecosystem has achieved TRL 9, the highest level of readiness. Thousands of trucks currently use unified battery platforms developed through national-level coordination between OEMs, CATL, State Grid, and infrastructure operators. Such alignment enables interoperability across brands and models, a feature repeatedly identified by interviewees as the decisive factor behind China’s rapid scaling. The literature further confirms that Chinese platforms have moved from prototype demonstration to stable, commercially operating systems, supported by mature BaaS business models and regulatory incentives that explicitly promote vehicle-battery decoupling.

In Europe, heavy-duty battery swapping remains between TRL 4 and 6. Interviews with engineers, policymakers and developers show that manufacturers continue to protect battery pack design as proprietary intellectual property, leading to incompatible mechanical formats, electrical architectures, thermal systems and BMS protocols. This fragmentation prevents the emergence of interoperable platforms and restricts systems to small-scale prototypes. The literature confirms that while European pilots demonstrate functional subsystem integration in controlled settings, they have not matured into multi-OEM or corridor-scale demonstrations due to the absence of unified standards and industry coordination.

The Nordics are at an even earlier stage, typically TRL 3-4. Interviews with public-sector stakeholders indicate growing interest in battery swapping, particularly due to grid-related concerns, but OEM participation is minimal and no on-road pilots exist. Literature similarly shows that although Sweden and Finland lead European charging infrastructure deployment, battery swapping has not yet been integrated into national policy frameworks, limiting progress to conceptual and feasibility-study stages.

In the United States, TRLs remain low (TRL 3-4). While companies such as Ample and Revoy have developed modular swapping concepts for light-duty vehicles, heavy-duty applications have not progressed beyond early demonstrations. Interviews reveal that policy and industry attention in the U.S. is focused primarily on megawatt charging and hydrogen, leaving battery swapping as a marginal niche. Literature similarly notes that the absence of corridor-scale demonstrations and OEM involvement keeps TRLs at early levels.

Japan and Australia occupy intermediate positions. Japan has achieved TRL 6-7 for medium-duty vehicles through automated robotic systems tested in real urban delivery conditions. Australia, by contrast, has reached TRL 6-7 primarily through retrofittable platforms deployed in mining and long-distance freight corridors. These deployments benefit from predictable routes and depot-based overnight operations, enabling operational feasibility even without cross-OEM standards. In this study, TRL levels reflect not only technical functionality but also evidence of sustained real-world operation, interoperability, and continuity of deployment across multiple sites. Table 1 summarises the assessed Technology Readiness Levels (TRLs) and deployment status of battery swapping for heavy-duty trucks across major regions, based on reported evidence of operational maturity, deployment scale, and interoperability.

Table 1. *Technology Readiness Level (TRL) and Deployment Status of Battery Swapping for Heavy-Duty Trucks by Region*

Region/ Country	**TRL (Final)**	**Evidence Basis**	**Notes**
China	TRL 9	Commercial multi-station operation; thousands of HDTs; fully automated 3-5 min swapping; standardised pack interfaces	Only fully mature ecosystem globally; interoperability achieved through national standards
Europe	TRL 4-6	Pilots and prototypes (E·HAUL , AkkuSwap, Designwerk); subsystem integration; early-stage demonstrations	OEM fragmentation, incompatible pack dimensions/BMS/voltages; no cross-OEM standards

Nordics (Finland, Sweden)	TRL 3-4	Concept studies, feasibility reports; *no pilots*; no OEM involvement	Interest from operators but no OEM engagement; no policy framework for swapping
United States	TRL 3-4	Early experimental concepts; limited HDT demonstrations; Ample/Revoy mainly LDV	Heavy-duty swapping not demonstrated at scale; focus on MCS and hydrogen in policy
Japan	TRL 6-7	Public-road automated pilot (MFTBC × Ample × Yamato) using robotic stations	Medium-duty focus; controlled real-road demo; limited scale, not commercial yet
Australia	TRL 6-7	Janus Electric retrofits in operational corridors; semi-automated swapping	Niche deployments; corridor-limited; no national standards or multi-OEM eco

Interpreting these disparities through the MLP highlights that TRL is not merely a measure of technical progress, but a reflection of niche-regime alignment. In China, strong alignment between niche innovations (automated swapping technologies) and the socio-technical regime (OEM architectures, battery standards, infrastructure investment systems, and supportive policy frameworks) allowed TRL advancement to accelerate rapidly. Landscape pressures, particularly national decarbonization goals and industrial policy, reinforced this alignment.

In Europe and the United States, however, regime structures characterized by proprietary OEM battery designs, entrenched charging standards, and fragmented regulatory frameworks prevent niche technologies from scaling, thereby constraining TRL development. These institutional lock-ins limit interoperability, hinder investment continuity, and reduce the likelihood of multi-OEM or corridor-scale demonstrations, even though the technology itself is mechanically viable.

The Nordics display even lower TRL progression due to the absence of OEM engagement and the lack of policy integration. Although logistics patterns in Finland and Sweden could benefit from high-utilization swapping systems, the technology remains at conceptual and feasibility-study stages.

Japan and Australia show intermediate levels of niche development, with progress restricted to specific operational contexts such as medium-duty delivery fleets (Japan) and retrofitted long-haul or mining operations (Australia). In both cases, scaling remains limited by the absence of unified standards and the restricted scope of current pilots.

Overall, these TRL disparities demonstrate that technological readiness is shaped primarily by socio-technical alignment rather than engineering maturity. China’s advancement to TRL 9 reflects a rare case of coordinated niche-regime-landscape alignment, whereas Europe, the United

States, and the Nordics illustrate how institutional fragmentation and regime-level resistance impede the progression of a technologically mature innovation. Japan and Australia occupy intermediate positions where partial alignment enables progress in specific niches but does not yet support widespread diffusion. Thus, TRL variation reflects differences in socio-technical coordination, not differences in technical capability.

4.4 The costs of the trucks and the Swapping Infrastructure

The economic feasibility of battery swapping for HDTs (HDTs) is shaped by two closely linked cost domains: (i) vehicle-level costs, including the battery system and ownership model, and (ii) infrastructure-level costs, comprising swapping stations, stationary battery inventory, and grid connection. Together, these elements determine total cost of ownership (TCO) outcomes and strongly influence the competitiveness of battery swapping relative to plug-in charging and other zero-emission pathways.

4.4.1 Vehicle and Battery Cost Structures

The literature consistently identifies the traction battery as the dominant cost component in battery-electric HDTs. Studies on long-haul and regional electric trucking in Europe and China show that large onboard battery capacities required for heavy-duty applications significantly increase vehicle CapEx and represent a major barrier to adoption (Shen & Mao, 2023).

Battery swapping is discussed in the literature as a mechanism to alter this cost structure by decoupling battery ownership from the vehicle. Instead of purchasing the battery as part of the truck, fleet operators may acquire the vehicle platform while accessing batteries through a service-based arrangement. The ICCT notes that such configurations can reduce upfront vehicle capital requirements, while shifting battery investment, degradation risk, and residual value to the swapping operator. However, the same studies emphasized that this cost shift does not eliminate battery costs but redistributes them from vehicle CAPEX to ongoing service expenditures (Bernard et al., 2022).

Outside China, published data on the purchase cost of battery-swappable HDTs remain limited. European studies report that the lack of standardized battery interfaces and the absence of series-produced swappable platforms contribute to higher unit costs and uncertainty compared with conventional battery-electric trucks designed around fixed battery packs.

4.4.2 Cost of Swapping Infrastructure

Battery swapping infrastructure for HDTs involves substantially higher capital investment than passenger-car swapping or conventional charging points. Infrastructure components typically include automated battery handling systems, stationary charging equipment, battery storage racks, transformers, and building structures, resulting in installations that resemble industrial facilities rather than simple refueling points (Bernard et al., 2022).

China

China provides the most comprehensive publicly available evidence on the costs of truck-oriented battery swapping infrastructure. Drawing on empirical analysis of Chinese deployments, Cui et al. (2023) report that medium-scale heavy-duty battery swapping stations require capital investments on the order of several million yuan, with a substantial share of total costs attributable to stationary battery inventory. This finding underscores the role of battery inventory as a dominant cost driver in truck-oriented battery swapping systems. The same analysis further emphasizes that per-swap costs decline sharply with increasing utilization, indicating that high-throughput, fleet-based operations are a prerequisite for economic viability (International Council on Clean Transportation [ICCT], 2023).

Beyond initial capital expenditure (CapEx), the literature highlights operational and lifecycle costs as critical determinants of economic performance in heavy-duty battery swapping systems. Recent modelling studies show that ensuring availability and operational continuity typically requires a substantial buffer of stationary batteries at swapping stations, often exceeding one-to-one vehicle-battery ratios or the number of batteries simultaneously in use. This additional inventory represents capital locked into stationary assets and makes total system costs highly sensitive to utilization levels (Cui et al., 2023; Wang et al., 2025).

Manufacturer specifications further illustrate the scale and technical complexity of heavy-duty swapping infrastructure. For example, the Enneagon GB 1.5 Promax 7+1 system is designed specifically for truck applications and integrates multiple high-power chargers, automated battery handling, and a power supply capacity in the megavolt-ampere range (Enneagon Energy, 2025). Although full installed system costs are not disclosed, these technical characteristics are consistent with the capital-intensive nature of heavy-duty battery swapping infrastructure identified in the literature.

Europe

In Europe, cost evidence is largely limited to pilot and feasibility studies. Nåbo et al. (2024), in a Swedish feasibility assessment, estimate annualized investment costs of approximately SEK 6-7 million (around €0.6-0.7 million) for a small-scale battery swapping facility serving a limited number of HDVs. Although significantly smaller than Chinese installations, this case illustrates that even pilot-scale infrastructure requires substantial capital commitment under European cost conditions, particularly due to grid connection and automation requirements.

4.4.3 Operational and Lifecycle Cost Considerations

Electricity procurement, maintenance of automated systems, and battery degradation further contribute to operating costs. While precise cost figures vary widely across studies and regions, there is broad agreement that the economic performance of battery swapping deteriorates rapidly under low utilisation conditions. While precise cost figures vary widely across studies and regions, there is broad agreement that the economic performance of battery swapping deteriorates rapidly under low utilisation conditions.“*The key issue is utilisation. Battery swapping works economically only* *when throughput is high and predictable; otherwise, the fixed costs cannot be recovered*." (Interviewee 3-C)

Conversely, high-utilisation logistics environments such as ports, mines, and dedicated freight corridors can leverage economies of scale and reduce cost per swap through intensive asset use (Nåbo et al., 2024; Li et al., 2024).

4.4.4 Integrated Cost Dynamics

Across the reviewed literature, a consistent finding is the strong interdependence between vehicle costs, infrastructure investment, and operational patterns. Battery swapping does not reduce system-level costs automatically; rather, it reallocates costs across vehicles, infrastructure, and service models. As a result, economic feasibility depends less on individual component prices and more on coordinated system design, high utilisation, and stable logistics demand (Shen & Mao, 2023).

These characteristics distinguish battery swapping from plug-in charging approaches, where infrastructure costs are more directly linked to grid reinforcement and peak power provision, and from hydrogen-based systems, which exhibit high system-level costs and efficiency losses (Bernard et al. 2022).

4.5 Implications of Battery Swapping for the Electricity Grid

This section does not present a grid simulation or a detailed power-flow model. Instead, it develops a conceptual load analysis based on transparent arithmetic to isolate and demonstrate a fundamental architectural difference between battery swapping stations (BSS) and megawatt charging stations. The analytical objective is deliberately narrow: to show how the decoupling of energy charging from vehicle service, enabled by intermediate battery storage, allows battery swapping to shift and flatten electrical load in ways that direct megawatt charging physically cannot achieve without additional, dedicated storage infrastructure. The term "model" is used here solely to describe a transparent accounting framework for tracking battery flows and charging activity, not a representation of physical grid behaviour.

4.5.1 Conceptual Load Analysis

The analysis abstracts from site-specific grid constraints and instead focuses on order-of-magnitude effects under consistent assumptions. Charging power levels, swap frequencies, and battery inventory sizes are therefore treated as illustrative parameters rather than predictive forecasts. This approach allows direct comparison of the load profiles associated with BSS and MCS configurations, highlighting their fundamentally different interactions with the electricity grid.

The conceptual load analysis developed in this thesis applies transparent, time-based arithmetic to estimate the electrical load imposed by a heavy-duty battery swapping station (BSS) over a 24-hour period. The objective is not to perform full AC power-flow calculations or evaluate detailed distribution-network behaviour; rather, the analysis focuses on the operational logic of the station. This makes it suitable for examining order-of-magnitude peak load, daily energy throughput, and the role of intermediate storage in shaping load profiles.

The analysis is intentionally designed as an order-of-magnitude screening exercise that captures operational causality, battery inventory, charger occupancy, and arrival-driven demand, rather than detailed network physics. This level of abstraction is appropriate for the research aim: to demonstrate peak-load behaviour, transformer stress under typical MV constraints, and the value of load shifting enabled by decoupled charging. Full power-flow and feeder-voltage analysis are therefore identified as a necessary next step for site-specific engineering design.

The analytical purpose of this conceptual analysis is therefore to answer four practical questions:

(1) What level of instantaneous peak load can be expected from a busy BSS?

(2) Would such a load exceed the capacity of a standard 3 MW medium-voltage transformer?

(3) How much electrical energy is delivered daily, and how does this compare with published data on European freight-charging infrastructure?

(4) Are the analytical outputs consistent with the ranges reported in scientific and technical literature?

To address these questions, the model tracks the flow of battery packs through the station, the charging and completion of battery cycles, and the evolution of available inventory. Hourly load is then calculated by summing the power drawn by all active chargers.

As a limitation, the model does not represent feeder impedance, voltage drops, harmonic effects, or protection constraints; therefore, results should not be interpreted as compliance evidence for any specific distribution grid, but as indicative magnitude and temporal pattern estimates.

Conceptually, the difference between MCS and BSS can be understood as an architectural contrast between instantaneous and buffered energy delivery. An MCS concentrates very high power demand directly at the point of vehicle service, analogous to a fire hose. The contribution of this analysis lies not in numerical precision, but in demonstrating an architectural property of energy delivery that direct megawatt charging cannot replicate without substantial, add-on storage infrastructure.

In contrast, a BSS accumulates energy gradually and delivers it to vehicles on demand, analogous to a water tower. The analysis estimates the stationary battery capacity required to perform this buffering function and demonstrates how such intermediate storage flattens peak load. While the numerical values are illustrative, the architectural principle of load decoupling constitutes the core finding.

4.5.2 Model Mechanics

The numerical values used in the model are not intended to represent a specific real-world station, but to define a plausible long-haul battery swapping scenario consistent with values reported in the literature and industry practice. Battery capacity, charger power, and station size were selected to reflect typical heavy-duty electric truck applications discussed in recent studies, while grid connection capacity represents a common medium-voltage constraint for industrial facilities. The model therefore serves as an illustrative system-level analysis rather than a site-specific design. Each truck uses a 450 kWh battery pack, which reflects capacities used in long-haul duty cycles. Chargers operate at a constant 350 kW, a simplification consistent with the modelling methods applied by Zhu et al. (2023), who also treat charger output as fixed. The station contains 12 chargers and is connected to the grid through a 3 MW transformer, a typical connection capacity for medium-voltage industrial facilities. Daily operation involves approximately 100 swap events based on the arrival pattern defined in the simulation model.

Table 2. *Model Assumptions and Simulation Outputs for Battery Swapping Station Grid Impact Analysis*

Indicator	Value	Explanation
Battery capacity per truck	450 kWh	Assumption for long-haul HDVs
Charger power	350 kW	Constant-power approximation
Number of chargers	12	Station capacity
Transformer capacity	3 MW	Local distribution constraint
Peak load	4.215 MW	Model output; exceeds transformer capacity
Overload duration	14 hours	Model output based on simulated demand profile (06:00-19:00)
Total daily energy consumption	≈65 MWh	Model output; sum of hourly energy demand
Arrival pattern	0-8 hours	increasing daytime logistics demand during the morning and early afternoon based on typical logistics activity
Total daily swaps	≈100	Based on arrival pattern
Unmet swaps	14 swaps (≈14%)	Model output due to charger saturation

Note: Values represent an illustrative long-haul battery swapping scenario. Input parameters are assumptions aligned with literature and industry practice, while peak load, overload duration, and unmet swaps are model outputs.

(1) Swap events

When trucks arrive, the model checks whether sufficient charged packs are available. Immediate swaps are performed whenever inventory is adequate; otherwise, unmet swaps are recorded.

(2) Activation of charging cycles

Whenever inventory falls below a predefined target level, additional charging cycles are started until either the target is restored, or all 12 chargers are occupied. Each new activation adds 350 kW to the station load. Charging continues for approximately 1.29 hours, rounded to two hours in the discrete hourly model.

(3) Completion of charging cycles

When a charging cycle finishes, the pack is returned to inventory, and the charger becomes available again.

(4) Load calculation

Hourly load is calculated as:

$$P_{station}(t) = N_{active}(t) \times P_{charger} + P_{aux}$$

An hour is defined as overloaded if the station load exceeds the 3 MW transformer capacity.

These simple rules create a realistic operational load curve without requiring complex electrical simulation.

Illustrative Example: Hours 0-5

The model logic can be seen clearly in the early hours of the day.

Hour 0: Inventory is high (12 packs), no swaps occur, and no chargers are active. Load = 15 kW.

Hour 3: Inventory begins to fall, the station starts activating chargers, and 3 chargers become active.

Load ≈ 1065 kW.

Hour 5: Arrival rates increase. Inventory falls, and more chargers activate until all 12 are in use (Appendix C).

4.5.3 Scenario A Results (Unmanaged Charging)

Under unmanaged conditions (Scenario A), the model shows that the station can draw a peak load of 4.215 MW,substantially higher than the 3 MW capacity of a typical medium-voltage transformer. This peak persists for approximately fourteen consecutive hours between 06:00 and 19:00, coinciding with the high-intensity arrival window of logistics operations. Daily energy consumption reaches approximately 64.8 MWh, a value consistent with the tens-of-megawatt-hour envelope reported by Shoman et al. (2023) for busy European charging hubs. The presence of unmet swaps (around 14%) further highlights that without controlled charging or larger inventory, charger saturation can constrain service capability. Figure 3 illustrates the daily load profile of a battery swapping station under unmanaged charging conditions (Scenario A), highlighting sustained multi-megawatt peak demand during core logistics operating hours.

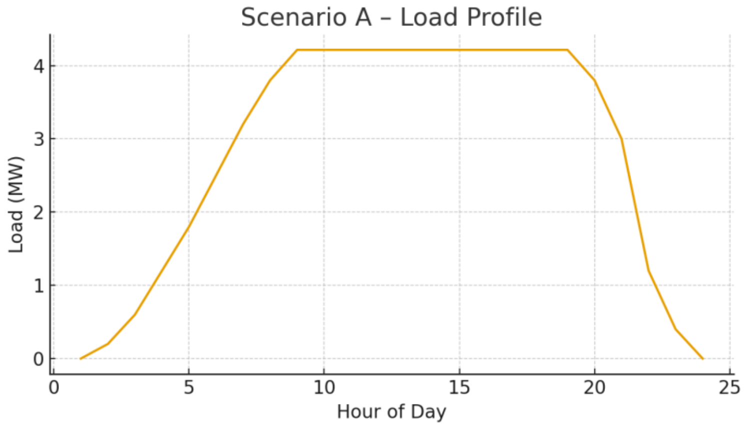


Figure 3. *Daily Load Profile of a Battery Swapping Station under Scenario A*

These findings align strongly with interview feedback: utility experts warned that “raw, uncoordinated truck charging will break the distribution grid,” and OEM stakeholders emphasised that large charging blocks require grid reinforcement unless buffering or load management is implemented.

4.5.4 Scenario B - Peak-Capped Managed Charging

Scenario B illustrates the structural advantage of battery swapping over megawatt charging: the decoupling of energy provision from the act of refuelling. By capping instantaneous grid load at 3 MW and redistributing battery charging into low-demand hours, the BSS can deliver the same total daily energy while avoiding transformer overload entirely. Crucially, the power cap applies only to grid-side charging, not to the swap operation itself. Because fully charged battery packs are buffered on site, vehicle service is determined by battery inventory rather than instantaneous grid power.

This shift is feasible because average energy requirements (≈2.7 MW over 24 hours) remain below the grid constraint, allowing all required charging to be completed within the capped limit when spread over time. As a result, peak demand is flattened, the load profile becomes smoother, the load factor increases to approximately 0.90, and no unmet swaps occur in the simulated scenario. Figure 4 illustrates the daily load profile of a battery swapping station under managed charging conditions (Scenario B), showing how peak demand can be capped at the grid connection limit while maintaining full service availability.

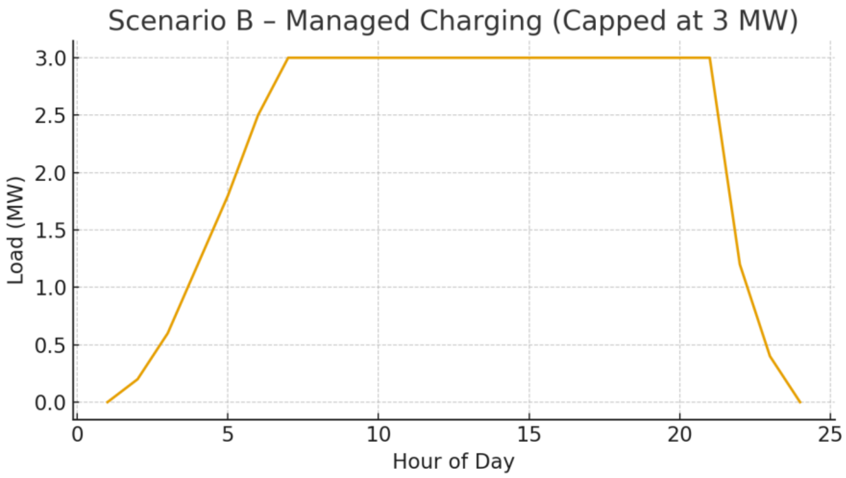


Figure 4. *Daily Load Profile of a Battery Swapping Station under Scenario B*

According to grid experts interviewed, this type of demand shaping is “practically impossible” with MCS corridors, where energy delivery must be synchronised with vehicle arrival and each charger can impose 1-2 MW peaks without local storage. Fleet operators similarly stressed that managed charging is “the only way our grid will survive mass electrification,” and found the inventory-buffering logic of BSS particularly compelling.

4.5.5 Validation of Model Outputs Using Real-World Studies

External validation confirms the realism of the model’s outputs. The peak value of 4.2 MW falls between the 3.6 MW and 7.2 MW peaks modelled by Zhu et al. (2022) for three-port and six-port high-power stations, suggesting that the magnitude of simulated demand is fully plausible for a medium-size facility. The overload duration mirrors the behaviour reported in multiple studies showing that even stations below 4 MW can violate feeder constraints (Zhu et al., 2022), while the overall peak range is consistent with Burges & Kippelt’s (2021) estimates of 1.8-10.1 MW for motorway charging sites[1] (Table 2).

Table 3. *Indicative model outputs (Scenario A - unmanaged charging)*

OUTPUT	VALUE	NOTES
PEAK LOAD	4.215 MW	Above 3 MW limit
OVERLOAD DURATION	14 hours	06:00-19:00

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1. Both studies focus on direct-charging (MCS/CCS) infrastructure, not battery-swapping. However, since both systems ultimately supply multi-megawatt charging power to large truck batteries, comparing the magnitude of electrical loads is appropriate and meaningful.

DAILY ENERGY	64.8 MWh	Sum of hourly demand
LOAD FACTOR	0.55	Based on peak load
UNMET SWAPS	14 (14%)	Due to charger saturation

The daily energy requirement aligns closely with real-world observations from Shoman et al. (2023), further reinforcing the reliability of the model's indicative results. This cross-validation demonstrates that although the conceptual analysis simplifies physical power flows, it captures the correct order of magnitude and dynamic profile of a functioning heavy-duty BSS.

Because the simulated peak loads and overload durations fall within ranges reported in comparable empirical and modelling studies, these quantitative results provide a valid basis for system-level interpretation. Taken together, the findings highlight three system-level implications. First, unmanaged charging at BSS stations can generate multi-megawatt peaks that exceed typical medium-voltage assets, confirming that grid constraints remain a central barrier for large-scale deployment an issue, repeatedly stressed by interviewees from utilities and public authorities. Second, the architectural design of battery swapping inherently provides flexibility: by maintaining inventory and charging batteries asynchronously, a BSS can operate as a controllable load, shifting consumption to off-peak periods without compromising fleet service quality. Such behavior aligns with the broader transition logic described in the MLP, where niche innovations offering system-level advantages such as load shifting can challenge incumbent charging regimes under growing landscape pressures like grid congestion and climate policy. Third, the capacity for grid-friendly operation depends on coordinated planning, appropriate transformer sizing, and potentially the integration of stationary storage or onsite generation elements that several experts noted are already emerging in Chinese stations equipped with behind-the-meter PV and load management algorithms.

In summary, battery swapping introduces both risks and opportunities for electricity networks. Without management, BSS facilities can impose prolonged multi-megawatt peaks that exceed distribution limits. But with even basic load controls, they can operate as predictable, shiftable loads that support network stability more effectively than megawatt charging. This duality reinforces the broader finding of the thesis: the advantages of battery swapping extend beyond operational performance to system-level benefits that become increasingly valuable as heavy-duty fleet electrification accelerates. These implications provide a critical foundation for the comparative assessment in RQ6 and the policy discussion in Chapter 5.

Battery swapping represents a new socio-technical capability within the heavy-duty transport system. By enabling controllable and flexible charging, it provides niches with the ability to manage energy demand in ways that differ fundamentally from conventional high-power peak-charging models. This flexibility directly challenges the current regime's dependence on rapid, grid-intensive charging solutions and instead offers an operational model that is better suited to system-level optimization. At the same time, battery swapping supports broader landscape-level pressures including the need for improved grid stability and greater integration of renewable energy sources.

Taken together, these features position battery-swapping systems as a socio-technical innovation that aligns closely with long-term energy-system transition trajectories, rather than merely serving as an alternative charging method.

4.6 Comparison with Alternative Electrification Pathways

The MCDA compares the relative performance of three technology pathways for HDT electrification battery swapping (BSS), megawatt charging, and hydrogen fuel-cell trucks (H_2-FC trucks) across seven criteria derived from literature and expert judgement. The evaluation integrates (1) a semi-quantitative scoring matrix based on evidence from peer-reviewed studies, technical reports, operational case studies, and interview insights, and (2) stakeholder-specific weighting vectors derived from four expert interviews representing academia, industry, logistics operators, and policy/regulation.

The aim is not to identify a universally optimal technology but to understand how alternative pathways perform across diverse operational, technical, economic, and system-level conditions.

Because the four weighting vectors reflect specific stakeholder roles and a Nordic-European context, the resulting composite ranking should be interpreted as context-bounded rather than globally representative. To reduce the risk of regional or role-driven bias, the study reports equal-weight and aggregated-mean scenarios and applies sensitivity and leave-one-out tests; these show the ranking is stable under moderate perturbations.

4.6.1 Criteria Selection

Criteria were selected through a triangulated process combining findings from the SLR, insights obtained from expert interviews, and operational and infrastructural requirements of heavy-duty trucking.

The procedure consisted of two elements: defining the evaluation criteria and scoring the technologies against these criteria (see Appendix B, Section B1 for swing ranges).

Table 4. *Evaluation criteria for assessing battery swapping vs. alternatives*

Code	Criterion	Description / Scope
C1	Operational Downtime	Swap/charge/refuelling time; flexibility

C2	Operational Expenditure	OpEx, Energy cost, service/usage fees
C3	Infrastructure CapEx	Station investment, grid connection
C4	Vehicle CapEx	Vehicle price, battery ownership model
C5	Grid Impact	Peak demand, load shifting potential
C6	Environmental Footprint	Lifecycle emissions, resource and material use
C7	TRL / Policy / Acceptance	Maturity, policy framework, user acceptance

These criteria collectively capture economic/operational performance, technical- infrastructural integration, and environmental sustainability, consistent with MCDA frameworks in energy system evaluation.

4.6.2 Scoring (Performance assessment)

Each technology (BSS, MCS, H_2-FC) was scored from 1 (lowest performance) to 5 (highest performance) relative to the others. Evidence for scoring came from peer-reviewed literature, industrial reports, operational data from pilot projects, and interview insights (Appendix B).

C1 - Operational Downtime

For operational downtime (C1), the evidence consistently indicates that battery swapping (BSS) performs best. Field experience from China shows swap cycles typically take 3-5 minutes (Cui et al. 2023). This was corroborated in interviews: an industry expert and a fleet operator noted that European pilots achieved ~10 minutes in early prototypes, with next-generation systems targeting ≤5 minutes. By contrast, megawatt charging requires ~30-45 minutes (Fraunhofer ISI & P3 Group, 2025), while hydrogen fuel cell refuelling typically takes ~10-15 minutes (H_2.Live Consortium, 2022). On this basis, BSS receives the top score (5/5) for C1, with hydrogen (4/5) and MCS (3/5) ranked lower due to longer stop durations.

C2 - Operational Expenditure (OpEx)

Across long-haul duty cycles, MCS tends to deliver the lowest energy cost per km due to grid electricity and high drivetrain efficiency (score 4/5) (Shen & Mao, 2023). BSS adds a station/service fee to the same electricity cost basis, partially offset by lower downtime (3/5) (Hao et al., 2025). Hydrogen remains the most expensive due to high production, compression, and distribution costs, leading to the lowest score (2/5) (IEA, 2022c, Wu et al., 2024).

C3 - Infrastructure CapEx

Hydrogen refuelling stations for HD trucks remain the most capital-intensive and O&M-heavy (1/5) (IEA, 2022c, Wu et al., 2024). BSS stations entail significant upfront cost due to robotics, inventory batteries and grid works (2/5) (Cui et al. 2023; interview evidence). MCS sites are generally cheaper per location but often require meaningful grid reinforcement (3/5) (Bernard et al., 2022).

C4 - Vehicle CapEx

With BSS, under battery-as-a-service (BaaS) models, fleet owners purchase the truck body without the battery, which reduces upfront capital requirements and improves capital efficiency for fleets; the battery swapping station operator provides access to charged batteries. (4/5) (Bernard et al. 2022). MCS-equipped long-haul trucks use very large battery packs (≈600 kWh+), leading to higher upfront vehicle costs (3/5) (Charged EVs, 2023). Hydrogen fuel-cell tractors remain the most expensive option due to high fuel-cell stack and high-pressure tank costs, combined with low production volumes, justifying the lowest cost score (2/5) (Basma et al., 2022).

To maintain consistency, operational expenditure (C2) was treated as recurring costs (e.g., energy, service fees, maintenance), while CapExs were captured separately under C3 (infrastructure) and C4 (vehicles). This separation was applied qualitatively, based on literature and interview insights.

C5 - Grid Impact

BSS enables off-peak/asynchronous charging and embedded buffer storage, mitigating peaks (4/5) (Liu & Danilovic, 2021; interview evidence). MCS can impose 1-2 MW per charger peak loads without local buffers (2/5) (Bernard et al., 2022), though static on-site storage can partly address this (noted in interviews). Hydrogen shifts electricity demand upstream to electrolysis; the net grid impact depends on production pathways (3/5) (IEA, 2022c).

C6 - Environmental Footprint

MCS and BSS share BEV well-to-wheel profiles; BSS may reduce materials through smaller average packs (4/5) (Togun, 2025; European Environment Agency, 2018; Liu & Danilovic, 2021). Hydrogen scores lower (2/5) where supply is fossil-based; green H_2 availability remains limited at scale (IEA, 2022c).

C7 - TRL / Policy / Acceptance

MCS enjoys strong alignment with EU/US standards and AFIR deployment targets (4/5) (AFIR, 2023; CharIN, 2025). BSS is commercially proven at scale in China (Electrive, 2021; Cui et al., 2023) but has limited standardisation and policy support in Europe/US (3/5) (ACEEE, 2025; Nåbo et al., 2024; interviews). Hydrogen receives policy attention, but HD truck TRL and station networks are still maturing (3/5) (Camacho et al., 2022; Ruf et al., 2020).

4.6.3 Expert-Based and Baseline (Equal/Mean) Weighting Scenarios

Expert-based weighting was intentionally limited to four interviews representing distinct stakeholder perspectives (academia, industry, logistics operators, and policy/regulation). The full interview sample was diverse but not numerically balanced across roles, with a higher representation of academic respondents. Deriving weights from all interviewees would therefore risk over-representing academic perspectives. Instead, one representative weighting vector was used for each decision-relevant stakeholder group to ensure balanced perspective-based aggregation rather than individual-based averaging. Expert-specific weighting vectors and swing ranges are reported in Appendix B.

Six primary weighting scenarios were evaluated: four representing the perspectives of the interviewed experts, one equal-weight scenario, and one aggregated-average scenario. Differences in weighting across experts are interpreted in light of their professional roles and decision-making contexts, rather than explicit verbal justification elicited during interviews. Table 4 summarizes the results.

Table 5. MCDA results under expert-based and baseline weighting scenarios for HDT electrification pathways

Scenario	BSS	MCS	H_2-FC	Ranking
Equal-weight	3.57	3.14	2.43	BSS > MCS > H_2-FC
Mean-weight (Aggregated)	3.56	3.20	2.45	BSS > MCS > H_2-FC
Expert - Academia	3.56	3.16	2.41	BSS > MCS > H_2-FC
Expert - Industry	3.63	3.22	2.56	BSS > MCS > H_2-FC
Expert - User/Operator	3.50	3.27	2.41	BSS > MCS > H_2-FC
Expert - Policy/Regulator	3.54	3.18	2.43	BSS > MCS > H_2-FC

The results show a clear and consistent pattern across all expert perspectives. Battery swapping (BSS) emerges as the top-ranked option in every scenario, largely because of its superior operational performance, particularly the ability to minimize downtime and maximize vehicle utilization. Interviewees from industry and fleet operators stressed that “downtime is our real bottleneck,” making the rapid energy replenishment enabled by BSS a decisive competitive advantage. This effect is amplified in corridor-based, multi-shift, or depot-centered operations where vehicles cycle through predictable routes. Interviewees also emphasized the advantages of battery-as-a-service models, which reduce upfront investment risks and improve fleet flexibility. In addition, the capability of BSS to decouple charging from vehicle arrival makes it a comparatively grid-friendly solution, especially in constrained distribution networks.

Megawatt and FC consistently hold the second position. Its strong performance is mainly driven by the high degree of interoperability between OEMs, the rapid progress in standardization (e.g., the emerging MCS interface), and the comparatively lower infrastructure capital costs. These characteristics make MCS an attractive and widely deployable option, particularly in regions with diverse fleets and strong policy support for charging infrastructure. Literature and interview evidence indicate that MCS is seen as the “default pathway” in Europe, where diverse fleets and fragmented market structures create significant barriers to cross-OEM swapping. Lower station CapEx further strengthens MCS’s position, although its operational downtime and grid impact remain less favorable than those of BSS.

Hydrogen fuel-cell systems (H_2-FC) remain in third place across all expert-based scenarios. Although hydrogen offers fast refueling and long driving ranges, technology currently faces structural disadvantages. High fuel prices, low well-to-wheel efficiency, and immaturity of refueling infrastructure all contribute to its lower overall score. Interviewees also pointed to uncertainties surrounding the scale-up of green hydrogen production and corridor-level infrastructure deployment. Interviewees from policy and research organizations underscored that “hydrogen simply cannot compete on energy efficiency,” and that near-term corridor deployment remains uncertain. These limitations outweigh the advantages of rapid refueling under current market conditions.

The inclusion of an equal-weight baseline scenario further reduces dependence on any single expert perspective and provides a neutral reference case.

Overall, the small numerical variation between expert scenarios (typically within ±0.1 points) indicates that the relative ranking of technologies is highly stable. This consistency suggests that the findings are not sensitive to individual expert weighting differences, reinforcing the robustness and reliability of the MCDA results.

4.6.4 Interpretation of Criterion-Level Results

The performance differences across the seven criteria help explain why battery swapping consistently achieved the highest overall MCDA score. Its superior downtime performance, enabled by 3-5-minute replenishment, gives it a clear operational advantage over both MCS and hydrogen refueling. Likewise, the ability to shift charging to off-peak periods reduces local grid impact, further strengthening its position.

MCS performed strongly in cost-related and system-level criteria. Its low infrastructure CAPEX, combined with high interoperability and rapid standardization progress, contributed to its stable second-place ranking across nearly all weighting scenarios. These characteristics make MCS particularly well aligned with Europe’s fragmented fleet structures and diversified logistics patterns.

H_2-FC trucks received the lowest scores across most criteria, reflecting structural limitations such as high fuel costs, low well-to-wheel efficiency, and the immaturity of refueling networks. These disadvantages outweighed the benefit of rapid refueling and long-range capability, leading to a consistent third-place ranking across expert-based and thematic scenarios.

Together, these patterns show that the ranking produced by the MCDA framework is grounded in clear performance differences across operational, economic, environmental, and technological dimensions, and remain stable across alternative weighting assumptions.

4.6.5 Insights from Interviews

Expert interviews provide critical context beyond the quantifiable MCDA scores. Industry representatives consistently emphasized that “grid constraints, not battery technology, are the true bottleneck.” In this regard, BSS and MCS diverge significantly. Swap stations, because of their ability to charge asynchronously, can actively mitigate grid peaks, while MCS sites often require major reinforcement to handle 1-5 MW loads per charger. An operator interviewed described BSS as “a controllable load with built-in buffers,” whereas MCS was characterized as “sharp, unavoidable demand spikes.” These qualitative insights help explain why certain criteria, particularly grid impact and operational downtime, carry disproportionate influence in the MCDA results.

Fleet operators stressed practical considerations: operational downtime, route predictability, and integration with logistics platforms. For many of them, the decisive advantage of BSS is not its technical novelty but its ability to “function without interfering with logistics.” Conversely, the flexibility of MCS makes it more attractive where fleets cannot be standardised or where operations are less centralised.

Policy and regulatory interviewees highlighted that European industrial and regulatory structures currently tend to favour MCS due to greater OEM alignment. By contrast, battery swapping is perceived as requiring a higher level of cross-industry integration, which remains difficult without regulatory intervention.

4.6.6 Robustness and Sensitivity Analysis

To ensure that the MCDA findings are reliable and not overly dependent on specific modelling assumptions, additional robustness and sensitivity checks were conducted. Since MCDA incorporates expert-derived weights and semi-quantitative scoring, it is essential to verify that the final ranking does not change when individual weights are adjusted or when a particular expert’s perspective is removed. Robustness tests therefore examine whether the results hold under alternative formulations of the weight vectors, while sensitivity analysis evaluates how moderate changes in the importance of each criterion influence the overall outcome. These procedures strengthen the internal validity of the MCDA and demonstrate that the conclusions are resilient to reasonable variations in assumptions. Detailed results of the sensitivity and leave-one-out tests are reported in Appendix A.

(1) ±20% Sensitivity on Each Criterion Weight

In the sensitivity analysis, each criterion within the mean-weight vector was individually adjusted by ±20% and the weights were subsequently renormalised. Despite these deliberately conservative perturbations, the ranking of technologies remained entirely unchanged across all fourteen sensitivity runs: battery swapping (BSS) consistently held the highest position, megawatt charging (MCS) remained second, and hydrogen fuel-cell systems (H_2-FC) persistently ranked third. This outcome demonstrates that the overall MCDA results are not driven by any single criterion and that moderate variations in weighting do not meaningfully influence the comparative performance of the three technological pathways.

(2) Leave-One-Out Expert Elimination

Each expert's weight vector was removed once, and the mean of the remaining three experts was used.

The results remained fully consistent across all four elimination scenarios. In every case, the ranking of technologies was unchanged, with battery swapping (BSS) maintaining the highest overall score, followed by megawatt charging and H_2-FC trucks. This stability indicates that the outcome of the MCDA is not dependent on any single expert’s weighting profile and that the comparative performance of the three pathways is inherently robust.

These two tests together demonstrate high internal stability, indicating that the MCDA results are not sensitive to moderate changes in assumptions or the inclusion/exclusion of individual experts, thereby strengthening confidence in the comparative conclusions presented in this chapter.

4.6.7 Integrated Interpretation of MCDA Findings

Taken together, findings across literature, interviews, and the MCDA framework suggest a context-dependent but consistent hierarchy. Battery swapping is optimal for high-utilisation, predictable logistics environments where downtime reduction and grid-flexible charging yield strong economic and operational benefits. Megawatt charging is the most scalable and OEM-neutral pathway, suited to heterogeneous fleets and distributed logistics networks typical of Europe and North America. Hydrogen fuel-cell trucks hold potential for specialised long-distance or energy-dense applications but remain constrained by cost, infrastructure, and energy-efficiency barriers. This hierarchy remains stable across alternative weighting and sensitivity scenarios.

From a MLP, each pathway can be interpreted as a competing niche attempting to scale under landscape pressures such as climate policy, rising energy prices, and grid congestion. Battery swapping challenges the incumbent charging regime by offering system-level advantages particularly load shifting while MCS aligns more closely with existing industrial architectures. Hydrogen remains a niche innovation whose uptake depends on broader energy-system transitions toward green hydrogen.

The comparison demonstrates that no single pathway dominates across all contexts. Instead, technologies exhibit differentiated strengths that align with distinct operational settings. Battery swapping is best positioned for structured, high-throughput applications; megawatt charging offers broad interoperability and scalability; and hydrogen retains conditional potential for specific long-range, high-payload use cases. As heavy-duty transport decarbonises, these pathways are likely to coexist, forming a hybrid zero-emission ecosystem rather than a single-technology landscape.

4.7 Challenges, Limitations, and Potential

Despite its clear operational and system-level advantages, battery swapping for HDTs faces a number of structural, economic, and institutional challenges that constrain its broader deployment outside a few highly coordinated ecosystems. The findings from the literature review and expert interviews indicate that these challenges arise not from the maturity of the technology itself, which multiple interviewees described as "already technically proven in specific operational contexts", but from the wider socio-technical environment within which the technology must operate. These challenges directly correspond to the MCDA criteria related to infrastructure cost (C3), vehicle cost (C4), and TRL/policy acceptance (C7), explaining the observed performance differences across technologies.

The most fundamental barrier is the persistent lack of standardization across OEMs. While China has achieved harmonized battery formats through policy coordination and industry alignment, European and North American manufacturers continue to rely on proprietary battery pack dimensions, cooling layouts, and BMS protocols. Interviewees repeatedly emphasized that "every OEM wants to impose its own system," creating fragmented designs that prevent interoperability and make cross-brand swapping infeasible. As highlighted in several studies, without standardised mechanical and digital interfaces, swapping networks cannot reach the utilisation levels required for commercial viability.

Infrastructure capital cost remains another major constraint. Fully automated truck-oriented swapping stations require significant investment in robotics, spare battery inventory, high-power chargers, safety systems, and grid connections. These costs are particularly high in regions where labor, land, or permitting processes are expensive. Literature estimates and interview evidence both indicate that these stations only achieve favorable economics in high-throughput logistics environments such as ports, mines, and fixed industrial corridors. Outside these contexts, utilization rates remain too low to justify multimillion-euro station investments, especially in the absence of long-term contractual commitments from fleet operators.

Battery ownership and trust concerns also pose challenges, particularly in open-access or multi-operator ecosystems. Operators in Europe and Australia voiced concerns about exchanging a known battery for an unfamiliar one with uncertain degradation history. Without robust state-of-health diagnostics, traceability systems, and transparent data-sharing arrangements, battery pooling can generate perceived or real inequality between users. Interviewees stressed that "nobody will swap unless they trust the system," highlighting the need for strong institutional governance and digital infrastructure.

Policy misalignment further limits scaling. Whereas China explicitly integrates battery swapping into national electrification strategies, offering incentives, land access, and regulatory support, policies in Europe and North America remain focused on FC and megawatt charging, leaving swapping outside mainstream planning frameworks. Stakeholders from public authorities in the Nordics and Germany explained that, even if interest exists, the lack of regulatory guidance makes it difficult for OEMs and investors to commit resources. This creates a feedback loop: without policy certainty, OEMs hesitate to standardize; without standardization, policymakers see limited grounds to intervene.

Despite these challenges, the findings also demonstrate substantial potential for battery swapping as a strategic component of heavy-duty electrification. The technology is particularly well-suited for predictable, high-utilization logistics environments such as port drayage, mining operations, industrial shuttles, postal fleets, and multi-shift depot-based delivery services. In these contexts, minimal downtime and predictable energy demand can unlock both operational and economic advantages.

From a grid perspective, battery swapping offers a uniquely flexible demand profile. Because energy delivery is decoupled from vehicle refueling, swap stations can shift charging to off-peak periods, reduce distribution-level congestion, and operate as controllable loads. Interviewees from utilities described swapping as “a buffer the grid actually needs,” reinforcing its potential role in emerging smart-grid, demand-response, and renewable-integration strategies. Studies further suggest that coupling BSS with solar PV, stationary storage, or energy-arbitrage models can reduce electricity costs and enhance system resilience.

Future technological trends are likely to further strengthen the case for swapping. Declining battery prices, improved automation, AI-driven scheduling, and more advanced cooling and diagnostic systems will reduce both capital and operational costs. As industry actors increasingly recognize the need for interoperable solutions and as regulatory bodies begin to consider multi-technology freight strategies, harmonized standards may emerge, addressing the most significant barrier identified in this study.

While unlikely to replace FC or hydrogen across all freight sectors, it holds clear strategic value as part of a diversified zero-emission ecosystem. Its most impactful role is expected in high-throughput, route-predictable operations where its strengths, minimal downtime, controlled charging, reduced grid impact, and the potential for battery-leasing models, directly align with operational and economic priorities. These insights set the stage for the broader discussion and policy recommendations presented in Chapter 5.

Viewed through the MLP lens, these challenges primarily reflect regime-level lock-ins and institutional misalignments, whereas the identified potential illustrate how, under the right niche support and landscape pressures, battery swapping can evolve into a strategically important component of the emerging zero-emission freight regime.

4.8 Chapter Summary

This chapter synthesised the empirical findings of the thesis by integrating evidence from the SLR, grey literature, expert interviews, the grid-impact model, and the MCDA. Together, these complementary sources provide a coherent and comprehensive understanding of the status, performance, and constraints of battery swapping in the electrification of HDTs.

The results show that battery swapping is a technologically mature and operationally advantageous solution, but one whose successful implementation depends heavily on ecosystem coordination. China remains the only region where the enabling conditions, standardization, OEM alignment, supportive policy frameworks, and high-throughput logistics have resulted in full commercialization. Interviews with stakeholders who have visited or collaborated with Chinese operators confirmed the scale and maturity of these deployments, characterizing the technology as “already used on a daily basis.” In contrast, Europe, the Nordics, and North America remain at early pilot stages due to fragmented battery designs, limited OEM cooperation, and policy frameworks that prioritize CCS and megawatt charging. These findings underline that technological readiness alone does not determine progress; institutional and industrial structures play an equally critical role.

The analysis of available battery-swapping technologies revealed substantial architectural diversity, with China’s automated behind-the-cab systems achieving the greatest maturity, while European side-loading or modular approaches remain at experimental TRL levels. Interviews consistently highlighted the mechanical and digital interface challenges that hinder interoperability, particularly around battery formats, cooling integration, and BMS communication protocols. These issues directly influence TRL progression and help explain why Europe remains in the TRL 4-6 range despite strong engineering capabilities.

Cost analysis showed that battery-swappable trucks remain more capital-intensive than plug-in BEVs, primarily due to modular pack interfaces and the requirement for automated infrastructure. However, Battery-as-a-Service (BaaS) models substantially reduce upfront vehicle CAPEX and shift financial risk from fleets to service providers. Infrastructure costs were found to be highly dependent on utilization levels, logistics contexts, and regional labor and permitting conditions. Both literature and interview insights stressed that utilization is the decisive variable for cost recovery, with high-throughput environments such as mines, ports, and depot-based logistics emerging as the most economically favorable settings.

The grid-impact assessment demonstrated that unmanaged charging at swap stations can generate multi-megawatt peaks capable of overloading standard medium-voltage connections. However, the unique architectural feature of battery swapping, the decoupling of charging from driving enables load shifting and controlled charging strategies that eliminate overloads even at high daily energy throughput. These findings were strongly supported by interviewees from utilities and grid operators, who saw BSS as a “controllable load” that could integrate effectively into local energy systems. This operational flexibility distinguishes swapping from megawatt charging, which imposes sharp power peaks that require extensive reinforcement.

The MCDA further confirmed the relative strengths and weaknesses of BSS, MCS, and hydrogen fuel-cell systems. Battery swapping consistently achieved the highest overall score across equal, aggregated, expert-based, and sensitivity-tested weighting scenarios. Its advantages stem from minimal downtime, high operational efficiency, and the potential for grid-friendly charging. Megawatt charging ranked second, reflecting its interoperability and policy alignment, while hydrogen remained third due to high fuel costs and immature infrastructure. The robustness tests demonstrated that these rankings remain stable across variations in assumptions, reinforcing the validity of the comparative findings.

Finally, the chapter identified several cross-cutting challenges including the absence of standardization, high station CAPEX, trust concerns related to battery ownership, and policy gaps that constrain large-scale adoption outside China. At the same time, the analysis highlighted considerable potential: battery swapping is particularly well suited to high-utilization, route-predictable operations, can support renewable integration, and may benefit from future cost reductions and emerging standards.

Overall, the findings depict battery swapping as a high-performance subsystem within the broader zero-emission freight landscape strategically valuable for specific logistics contexts but dependent on coordinated action among OEMs, policymakers, utilities, and operators. These insights form the foundation for the broader interpretation and policy discussion presented in Chapter 5.

Interpreted through the MLP, the future role of battery swapping is shaped less by technological breakthroughs and more by the alignment of niche innovations, regime structures, and landscape-level pressures across different regions and logistics contexts.

5 RESULTS AND DISCUSSION

5.1 Introduction to the Discussion

This chapter interprets the empirical findings by situating them within broader socio-technical, institutional, and policy contexts. While Chapter 4 focused on reporting evidence derived from the SLR, grey literature, expert interviews, the grid-impact model, and the MCDA, Chapter 5 shifts the focus from description to explanation by analyzing how and why these findings emerge and what they imply for the future electrification of heavy-duty freight transport.

This interpretive step follows directly from the research design outlined in Chapter 3. The research questions extend beyond technical performance to encompass regional technology readiness, market adoption, infrastructure and grid interaction, institutional coordination, and competing electrification pathways. As a result, a purely technical reading of the results is insufficient. Instead, a socio-technical perspective is required to explain why battery swapping achieves commercial maturity in some contexts while remaining marginal in others, despite comparable underlying technologies.

Building on the evidence reviewed in Chapter 2 and analyzed in Chapter 4, a clear regional divergence emerges. Based on the evidence reviewed in Chapters 2 and 4, this thesis assesses battery swapping as having reached full commercial deployment in China (approximately TRL 9). In contrast, Europe is characterized by fragmented pilot projects (approximately TRL 4-6), while the Nordics and the United States remain at earlier stages (approximately TRL 3-4), marked by weak OEM engagement and competing investments in megawatt charging and hydrogen. The evidence indicates these differences cannot be explained by technological feasibility alone, since the core battery swapping technology is available across regions.

To interpret this mismatch between technological capability and real-world adoption, this chapter applies the MLP as its primary analytical framework. Introduced in Chapter 3 and grounded in transition studies literature reviewed in Chapter 2, the MLP provides a structured lens for examining how niche innovations interact with dominant socio-technical regimes under broader landscape pressures. By explicitly linking the empirical findings to the landscape, regime, and niche levels, this chapter clarifies how policy signals, industrial coordination, infrastructure planning, and logistics characteristics jointly shape the prospects of battery swapping.

5.2 Interpretation Through the MLP Framework

Results suggest a persistent mismatch between the technological capabilities of battery swapping and its uneven real-world deployment across regions. While the technology demonstrates high operational performance and, in some contexts, full commercial maturity, its adoption remains geographically concentrated and institutionally constrained. To interpret this divergence, this section applies the MLP as the primary analytical framework.

As outlined in Chapter 3 and grounded in the transition studies literature reviewed in Chapter 2, the MLP conceptualizes socio-technical change as an interaction between niche innovations, dominant regimes, and broader landscape pressures. Rather than serving as a purely theoretical lens, the application of the MLP in this chapter is empirically motivated. Evidence consistently shows that regional differences in battery swapping deployment cannot be explained by technological readiness alone.

Across China, Europe, and North America, similar battery swapping technologies are technically available, yet they reach markedly different Technology Readiness Levels (TRLs). Interview data reinforce this pattern, with multiple experts emphasizing that technological maturity is not the primary constraint, pointing instead to gaps in coordination among actors, standards, and infrastructures. In parallel, the grid-impact model and MCDA indicate that battery swapping performs strongly in terms of operational uptime, load flexibility, and total cost of ownership in specific use cases, even in contexts where market uptake remains limited. Together, these findings indicate that adoption outcomes are shaped by socio-technical structures rather than performance metrics alone.

Within the MLP framework, the empirical results can be systematically interpreted across the three analytical levels. Landscape-level pressures are reflected in climate policy targets, energy price dynamics, and national industrial strategies, which create a general push toward zero-emission freight but do not uniformly favor battery swapping over competing pathways. Regime-level dynamics arise from the behavior of incumbent actors, including OEMs, utilities, regulators, and fleet operators, whose established practices, investment logics, and regulatory expectations stabilize particular technological trajectories. Niche-level dynamics emerge in context-specific applications such as ports, mines, and regional logistics corridors, where battery swapping demonstrates clear operational advantages but remains spatially and institutionally bounded.

By organizing empirical evidence within this multi-level structure, the MLP enables a coherent interpretation of why battery swapping scales successfully in some regions while stagnating in others. It highlights how alignment or misalignment across policy signals, industrial coordination, infrastructure investment, and logistics characteristics shapes transition outcomes. In doing so, this approach directly supports the central objective of the thesis: to assess not only the current status of battery swapping technology, but also its potential role within the broader transition toward zero-emission heavy-duty transport.

This case demonstrates that for capital-intensive infrastructural technologies, niche scaling requires not just regime weakness, but the active construction of a counter-regime, a parallel ecosystem of aligned standards, finance, and actors, as seen in China. Europe's failure is a failure of counter-regime construction.

5.2.1 Landscape Pressures

The findings indicate that landscape-level pressures generate a strong and growing push toward the decarbonization of heavy-duty freight transport, yet they do not uniformly favor battery swapping as a specific technological pathway. Climate policy, energy system considerations, and industrial strategy collectively shape the opportunity space within which alternative electrification solutions compete.

Across all regions examined, climate policy functions as a dominant landscape driver by establishing binding decarbonization objectives for heavy-duty transport. In Europe and the United States, these policy frameworks accelerate electrification in general but remain largely technology-neutral. As a result, they reinforce incumbent and highly visible solutions, such as conventional CCS-based charging and emerging megawatt charging, without providing directional support for system-level alternatives like battery swapping. This neutrality limits the ability of landscape pressures to destabilize existing infrastructure trajectories.

China presents a contrasting landscape configuration. National industrial strategies explicitly align freight decarbonization with domestic battery production, energy security objectives, and coordinated infrastructure deployment. Policy instruments, including standardization mandates, support for battery-as-a-service models, and preferential land allocation for swap stations, create a landscape in which battery swapping is actively prioritized rather than merely permitted. This directional alignment reduces uncertainty for regime actors and facilitates rapid scale-up.

Energy system dynamics further differentiate regional contexts. Electricity price volatility and concerns over peak demand heighten sensitivity to high-power charging solutions in regions with constrained grids. The grid-impact model in Chapter 4 demonstrates that megawatt charging intensifies peak load pressures, whereas battery swapping enables temporal decoupling between vehicle operation and battery charging. Despite this systemic advantage, landscape-level energy strategies in Europe and the United States continue to prioritize high-power charging corridors, suggesting that political signaling and infrastructure narratives outweigh grid-efficiency considerations at this level.

Industrial strategy emerges as a decisive landscape factor shaping divergent outcomes. In China, state-led coordination across OEMs, battery manufacturers, and utilities establishes a stable macro-environment for standardized swapping systems. In contrast, industrial strategies in Europe and North America emphasize market competition, OEM autonomy, and incremental infrastructure expansion. These priorities reinforce existing technological pathways and constrain the emergence of alternative system architectures such as battery swapping.

Taken together, the landscape-level analysis shows that battery swapping does not stagnate due to unfavorable macro-level pressures. Instead, its limited deployment outside China reflects the absence of directional landscape signals capable of supporting coordinated system change. Where climate policy, energy strategy, and industrial planning align, battery swapping benefits from a stable and enabling landscape. Where such alignment is lacking, landscape pressures remain insufficient to displace incumbent regimes or elevate battery swapping beyond a niche role.

5.2.2 Regime Dynamics

The empirical findings indicate that regime-level dynamics play a decisive role in constraining the expansion of battery swapping outside a limited set of contexts. While landscape pressures create a general push toward electrification, it is the socio-technical regime, comprising incumbent actors, established rules, and infrastructural commitments, that stabilizes specific technological pathways and marginalises alternatives.

Across Europe and North America, the heavy-duty transport regime is characterized by strong OEM autonomy and proprietary vehicle architectures. Evidence from interviews and industry analysis shows that battery systems are closely integrated into vehicle design and are treated as a core element of competitive differentiation. As a result, OEMs exhibit strong resistance to standardized, swappable battery interfaces. This reluctance is not driven by technical infeasibility but by concerns over intellectual property, brand identity, and control over performance optimization.

Infrastructure planning further reinforces this lock-in. Utilities and infrastructure providers base grid upgrades and investment strategies on established and emerging charging standards, particularly CCS and megawatt charging. Regulatory frameworks, such as AFIR in the European Union and NEVI in the United States, institutionalize these standards by embedding them into funding mechanisms and long-term infrastructure plans. The policy review demonstrates that battery swapping is largely absent from these frameworks, effectively excluding it from regime-level legitimacy despite its demonstrated technical maturity in other regions.

Fleet operators, as regime actors, further stabilize incumbent pathways through expectations and risk perceptions. Interview evidence indicates that many operators perceive CCS and MCS as the “default future” for BETs, largely because these options align with OEM roadmaps and publicly supported infrastructure. In contrast, battery swapping is often viewed as uncertain or experimental, not due to performance limitations, but because it lacks visible regime endorsement and long-term policy commitment.

In China, regime dynamics differ fundamentally. Vertically integrated supply chains, coordinated OEM participation, and the involvement of state-owned utilities reduce fragmentation and enable standardization. As shown in Chapter 4, these conditions allow battery swapping to transition from a niche solution to a regime-compatible infrastructure component. The alignment of OEM strategies, utility planning, and regulatory support lowers adoption risk and facilitates rapid scaling.

Taken together, the regime-level analysis explains why battery swapping remains marginal in regions where technological performance alone would justify broader deployment. The findings indicate that regime stability, reinforced by OEM lock-in and infrastructure path dependence, constitutes a primary barrier to diffusion. Without deliberate interventions to disrupt these stabilizing mechanisms, such as standardization mandates, targeted policy support, or coordinated pilot programs, battery swapping is unlikely to challenge incumbent charging regimes, regardless of its technical or economic advantages.

5.2.3 Niche-Level Dynamics

The empirical findings indicate that battery swapping currently functions primarily as a high-performance niche innovation rather than a broadly diffused regime solution outside China. Niche momentum is strongest in operational settings where utilization is high, routing is predictable, and fleet coordination is feasible, such as ports, mines, industrial shuttles, and depot-centered multi-shift operations. In these bounded contexts, battery swapping demonstrates clear advantages in operational uptime and grid-manageable charging, allowing niche experiments to translate into measurable performance and business value.

However, niche expansion remains constrained by limited opportunities for cross-fleet standardization and by the need for coordinated infrastructure governance. This creates a structural challenge: the very conditions that make swapping highly effective (standardization and coordination) are difficult to achieve in fragmented markets. As a result, battery swapping niches outside China tend to remain spatially bounded and institutionally dependent, even when the underlying technology is available.

In this transition landscape, battery swapping niches also develop alongside other niche trajectories, most notably megawatt charging and hydrogen fuel cells. The next section therefore examines how these competing niches gain legitimacy and resources through different forms of regime and policy alignment, shaping the opportunity space for battery swapping.

5.2.4 Why Battery Swapping Scaled in China but Stalled in Europe

The divergent deployment trajectories of battery swapping identified in Chapter 4 can be explained by differences in alignment across the three levels of the MLP. Comparative evidence shows that battery swapping scales where landscape pressures, regime structures, and niche conditions reinforce one another, and stagnates where such alignment is weak or absent.

In China, strong alignment is observed across all three socio-technical levels. At the landscape level, national industrial strategy, energy security objectives, and climate policy generate a clear and directive signal favoring electrification pathways that support domestic battery manufacturing and infrastructure control. Battery swapping is not merely tolerated within this framework but actively prioritized as a strategic solution. At the regime level, vertically integrated supply chains, coordinated OEM participation, and the involvement of state-owned utilities reduce fragmentation and enable standardization, lowering uncertainty for investors and operators. At the niche level, high-utilization logistics environments, such as ports, mines, and regional freight corridors, provide favorable conditions for demonstrating operational reliability and economic viability. The mutual reinforcement of these levels explains why battery swapping in China has reached full commercial maturity (TRL 9).

In contrast, the European context is characterized by persistent misalignment across MLP levels. While climate policy creates strong landscape pressure for decarbonization, it remains largely technology-neutral and does not provide directional support for battery swapping. At the regime level, fragmented OEM strategies, proprietary battery architectures, and regulatory frameworks centered on CCS and emerging megawatt charging stabilize incumbent technological pathways. These conditions limit the legitimacy of alternative system architectures and constrain battery swapping to isolated pilot projects. At the niche level, heterogeneous and decentralized logistics markets reduce the likelihood of achieving the high utilization rates required for economic viability, preventing niche experiments from scaling beyond intermediate readiness levels (TRL 4-6).

Comparable dynamics are evident in the Nordic countries and the United States, albeit with additional constraints. In the Nordics, limited freight density, the absence of domestic HDT OEMs, and weak policy recognition restrict niche development, resulting in early-stage maturity (TRL 3-4). In the United States, policy attention and investment focus primarily on megawatt charging and hydrogen, while fragmented OEM strategies and corridor-based logistics limit the feasibility of shared swapping infrastructure. In both cases, battery swapping niches fail to secure sustained regime support despite favorable performance in specific applications.

Overall, this comparative analysis demonstrates that the uneven adoption of battery swapping cannot be attributed to technological limitations. Instead, it reflects region-specific patterns of socio-technical alignment. Where landscape signals provide direction, regimes enable coordination, and niches offer high-throughput use cases, battery swapping can scale rapidly. Where these conditions are misaligned, the technology remains confined to experimental or marginal roles. This synthesis confirms the explanatory value of the MLP framework and clarifies why battery swapping has achieved commercial success in China while remaining stalled in Europe and other Western contexts.

5.3 Competing Niches: MCS and Hydrogen

Building on the niche-level interpretation above, this section analyses how MCS and hydrogen function as competing niches and why they attract different forms of institutional support. The empirical findings indicate that battery swapping does not evolve in isolation, but competes with alternative zero-emission pathways that are simultaneously positioned as niche innovations within the heavy-duty transport transition. In the regions examined, MCS and H_2-FC trucks represent the most prominent competing niches, each benefiting from different forms of regime and landscape support.

Megawatt charging aligns closely with existing socio-technical regimes in Europe and North America. As shown in Chapter 4, MCS builds directly on current BET architectures and extends established CCS-based charging paradigms rather than challenging them. This compatibility significantly lowers transition costs for OEMs and infrastructure providers. OEM roadmaps, regulatory frameworks, and infrastructure planning processes increasingly converge around MCS, reinforcing its position as the preferred scaling pathway for long-haul BETs. Policy instruments such as AFIR in the European Union and NEVI-funded programs in the United States explicitly anticipate megawatt-scale charging, granting MCS early regime legitimacy even before large-scale deployment is achieved.

From an operational perspective, the findings show that MCS offers flexibility and interoperability advantages, particularly for heterogeneous fleets and open-access corridors. However, the grid-impact analysis presented in Chapter 4 highlights a critical limitation: high-power charging introduces structural peak demand challenges that intensify pressure on local distribution networks. Despite these constraints, MCS continues to attract investment and policy attention, indicating that regime compatibility and infrastructural continuity outweigh grid efficiency considerations at this stage of the transition.

H_2-FC trucks constitute a fundamentally different niche, sustained primarily by long-term political signaling and industrial strategy rather than near-term operational performance. The literature and policy analysis show that hydrogen benefits from its perceived suitability for long-range transport and fast refueling. Nevertheless, empirical evidence consistently points to weak economic competitiveness, low energy efficiency, and significant infrastructure barriers. Hydrogen’s position as a competing niche is therefore less a reflection of current feasibility and more an outcome of strategic hedging by policymakers and industry actors seeking to diversify technological options under uncertainty.

In comparison, battery swapping occupies a distinct competitive position. Unlike MCS, it challenges prevailing vehicle architectures and infrastructure logics, requiring deeper coordination across OEMs, utilities, and fleet operators. Unlike hydrogen, it demonstrates strong operational and economic performance in specific use cases, supported by real-world deployment evidence. However, as shown in Chapter 4, battery swapping lacks the regime-level endorsement that elevates MCS and hydrogen within policy and investment agendas in Europe and North America.

The interaction between these competing niches explains why battery swapping struggles to gain visibility despite favorable performance metrics. MCS benefits from incremental compatibility with incumbent systems, while hydrogen is protected by strategic narratives and long-term policy commitments. Battery swapping, by contrast, requires system-level reconfiguration and therefore faces higher institutional resistance. This competitive imbalance reinforces the path dependence identified in Section 5.2 and limits the conditions under which battery swapping can transition from a niche solution to a mainstream alternative.

Overall, the analysis of competing niches demonstrates that adoption outcomes are shaped less by comparative technological performance than by alignment with dominant regime structures and policy expectations. Battery swapping’s future role is therefore not determined solely by its technical or economic merits, but by whether it can secure institutional recognition alongside, or in combination with, megawatt charging and hydrogen within a diversified zero-emission freight ecosystem.

5.3.1 Cross-RQ Integrated Interpretation

Synthesizing the evidence across RQ1-RQ6 positions battery swapping as a high-performance electrification pathway whose diffusion is governed more by socio-technical alignment than by technological capability alone. The findings from the literature review, case studies, interviews, grid-impact modelling, and MCDA converge on a consistent pattern: battery swapping delivers strong operational and system benefits in well-defined contexts, yet its adoption remains contingent on coordination among OEMs, infrastructure actors, and policymakers. This integrated interpretation explains the observed divergence between regions where battery swapping has scaled to commercial maturity and regions where it remains limited to pilots or early feasibility stages.

5.3.2 Technology Judgement: Mature but System-Dependent

Across the reviewed evidence, battery swapping emerges as technologically mature in settings where system integration has been achieved. In China, the technology operates at full commercial readiness (TRL 9), supported by standardized interfaces, established station operations, and large-scale fleet deployment. Outside China, the technology base is largely available but remains at lower TRLs because the enabling system conditions, common interfaces, coordinated deployment models, and stable regulatory recognition, are not yet in place. The results therefore indicate that battery swapping’s maturity is not solely a function of engineering performance; it is system-dependent and requires harmonization among OEM architectures, operational protocols, and infrastructure governance to progress beyond experimental or pilot-level deployment.

5.3.3 Economic Interpretation

The economic findings show a clear trade-off: battery swapping requires higher upfront CapEx, driven by station infrastructure and battery inventory, yet can provide favorable total cost of ownership in high-utilization and predictable logistics environments. Evidence indicates that swapping becomes economically attractive where vehicles operate in multi-shift patterns and where routing is stable enough to ensure high station throughput, such as ports, mines, regional industrial corridors, and depot-based delivery fleets. In these cases, reduced downtime, improved utilization, and battery-as-a-service arrangements can offset infrastructure costs and stabilize fleet cash flow. Conversely, in heterogeneous fleets, fragmented logistics markets, and low-volume regions, utilization levels are insufficient to amortize fixed infrastructure costs, limiting economic viability and contributing to the stalled deployment observed in Europe and other Western contexts.

5.3.4 Grid Interpretation

The grid-impact findings provide a distinctive system-level insight. Results from the grid model, supported by literature and interview evidence, show that battery swapping enables managed and time-shifted charging, thereby reducing local peak demand and mitigating congestion in constrained distribution networks. In contrast, Megawatt charging introduces structural peak-load challenges that often necessitate costly grid upgrades. Hydrogen pathways shift electricity-system burdens upstream through electrolysis and supply-chain energy requirements, rather than eliminating them. This indicates that battery swapping is uniquely grid-flexible among the compared options, with strong relevance for regions where grid reinforcement is slow, expensive, or politically contentious. However, the findings also show that this technical advantage does not automatically translate into adoption when policy and infrastructure regimes remain oriented toward corridor-based high-power charging investment.

5.3.5 Comparative Performance Interpretation

The MCDA results reinforce and stabilize the integrated interpretation. Across weighting scenarios, battery swapping consistently ranks highly due to its operational uptime, grid flexibility, and strong performance in predictable high-throughput logistics. Megawatt charging ranks strongly on interoperability and scalability within existing BEV truck architectures, reflecting its regime compatibility. Hydrogen remains comparatively weaker due to economic and infrastructure constraints, although it retains niche relevance in long-range applications where political and industrial strategies maintain support. Importantly, the analysis highlights a mismatch between MCDA rankings and observed deployment patterns, indicating that real-world technology selection is shaped not only by performance optimization but also by institutional alignment, regulatory expectations, and infrastructure path dependence.

5.4 Policy and Industry Implications

The analysis reveals a central paradox: battery swapping is a technically mature and system-efficient solution that struggles within institutional environments not yet designed to accommodate it. Across the regions examined, its future depends less on further technological development and more on deliberate ecosystem coordination and governance alignment. The findings indicate that without aligned standards, infrastructure planning, and credible demand commitments, battery swapping cannot compete on a level playing field, even where it delivers strong operational uptime and grid flexibility.

The interventions outlined below are not conceived as subsidies, but as governance instruments aimed at correcting coordination failures that arise in the deployment of capital-intensive, system-level electrification technologies. While the specific institutional actors and regulatory frameworks differ across jurisdictions, the underlying policy logic is broadly applicable across regions. The examples below draw most explicitly on the European context, where regulatory responsibilities are clearly delineated, but the principles extend to other national and regional settings.

Rather than relying on top-down or authoritarian standardisation, several targeted governance levers can reduce coordination failures while preserving market competition:

- Transport authorities responsible for heavy-duty infrastructure planning (e.g. EU transport authorities under AFIR) could introduce time-limited battery-swapping pilot corridors. Such instruments would allow temporary regulatory flexibility and targeted support for interoperable heavy-duty truck swapping demonstrations in high-utilisation nodes such as ports, mines, and logistics parks, where utilisation levels are sufficient to test system-level viability under real operating conditions.
- Energy and grid authorities could enable fast-track grid connection procedures and flexibility contracts for battery swapping stations that commit to peak-capped charging and provide verifiable demand-response services. Treating swapping stations as controllable industrial loads, rather than as passive electricity consumers, would better reflect their system-level grid value and reduce unnecessary connection barriers.
- Standardisation bodies could support pre-standardisation efforts focused on defining minimum viable interfaces required for interoperability, including mechanical envelopes, high-voltage connectors, battery management system communication, and thermal coupling. Prioritising battery-agnostic communication and safety requirements, rather than full battery pack uniformity, would lower entry barriers while preserving scope for technological diversity and competition.
- Public procurement authorities could leverage purchasing power by requiring interoperability-ready designs or Battery-as-a-Service compatibility in publicly supported zero-emission truck deployments, particularly in port drayage, industrial logistics, and municipal heavy-duty fleets. Such requirements can function as demand-aggregation mechanisms, guaranteeing baseline utilisation and long-term demand commitments during early deployment phases and helping to overcome coordination failures between OEMs, infrastructure providers, and fleet operators.

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5.4.2 Implications for Industry Actors

For OEMs, the analysis highlights standardization as a strategic rather than purely technical decision. While proprietary battery architectures currently support differentiation, they also constrain market expansion for battery swapping and limit participation in high-utilization logistics hubs. Developing battery swapping-ready platforms, even for limited applications, could unlock new customer segments and provide a competitive advantage in contexts where uptime and utilization are critical.

For fleet operators, battery swapping offers a pathway to reduce upfront vehicle investment and stabilize operating costs through battery-as-a-service models. The findings show that swapping can significantly enhance vehicle utilization and reduce downtime in predictable, high-throughput operations. However, these benefits are contingent on access to coordinated infrastructure and long-term policy support, underscoring the importance of engagement with OEMs and public authorities during pilot and deployment phases.

For utilities, battery swapping represents an opportunity rather than a burden. Unlike high-power charging, swapping stations provide controllable and shiftable demand that can be aligned with grid constraints and renewable generation profiles. The results suggest that utilities could play an active role in co-developing demand-response programs and grid services in partnership with battery swapping operators, positioning swapping stations as flexible assets within the electricity system.

5.5 Limitations

This study acknowledges several limitations that should be considered when interpreting the results. These limitations are explicitly identified and methodologically justified, and they do not undermine the internal coherence or validity of the findings. Rather, they reflect current empirical constraints and institutional conditions shaping research on emerging heavy-duty electrification pathways.

First, the grid-impact assessment relies on a simplified modelling framework rather than a full power-flow simulation. This approach was deliberately chosen to enable a consistent comparative analysis of battery swapping, megawatt charging, and hydrogen pathways. While the model does not capture detailed distribution-level effects such as voltage deviations or local congestion, it robustly represents relative differences in peak demand, load flexibility, and system stress. Grid-related results should therefore be interpreted as comparative and explanatory rather than as site-specific operational predictions.

Second, the empirical basis for battery swapping deployment in Europe remains limited due to the absence of large-scale commercial operations. Consequently, the analysis draws on early-stage demonstrations, feasibility studies, and structured comparisons with the Chinese context. This limitation reflects the current deployment landscape rather than a deficiency in research design and is directly relevant to the study’s objective of explaining why battery swapping remains stalled in Europe despite apparent technical maturity.

Third, the qualitative interview sample is limited in size, although it spans a diverse set of stakeholders, including OEMs, infrastructure providers, policymakers, and system integrators. The interviews are not intended to support statistical generalisation but to enable analytical triangulation. The recurrence of core themes, such as coordination failure, standardisation barriers, and regime lock-in indicate sufficient thematic saturation for the purposes of this study.

Fourth, the systematic literature review exhibits a geographic concentration on China and Europe. This reflects both the maturity of battery swapping deployment in China and the policy relevance of the European context. Developments in other regions may therefore be underrepresented, particularly where battery swapping remains at a conceptual or exploratory stage.

Most critically, a high-priority and unresolved limitation concerns insurance, liability, and warranty allocation under battery-as-a-service (BaaS) and pooled battery regimes. Unlike plug-in charging, battery swapping decouples the battery from the vehicle and redistributes operational and legal risk across OEMs, station operators, and fleet owners. Responsibilities related to thermal incidents, battery degradation, state-of-health verification, and residual-value guarantees cannot be clearly allocated within existing insurance and warranty frameworks, which are largely based on integrated vehicle ownership models inherited from internal combustion and conventional battery-electric paradigms.

This institutional configuration creates a structural mismatch that cannot be resolved through technical performance improvements alone and may function as a form of socio-technical lock-in protecting incumbent vehicle-battery integration models. While this study identifies liability and ownership ambiguity as a potentially decisive barrier to large-scale battery swapping deployment, it does not develop or test alternative legal or insurance arrangements. Addressing this gap requires dedicated institutional, legal, and actuarial research, ideally informed by real contractual structures and claims data from pilot deployments. Such research could include comparative case studies of contractual arrangements in existing pilot projects, analysis of warranty and liability allocation across OEMs, operators, and insurers, and structured stakeholder workshops involving regulators, insurers, and fleet operators.

Finally, the rapidly evolving nature of heavy-duty electrification technologies and policy frameworks constitutes a structural limitation. Standards, infrastructure strategies, and regulatory priorities are subject to change, which may influence the applicability of specific findings over time. The conclusions should therefore be interpreted as analytically grounded within the current transition phase rather than as fixed long-term forecasts

5.6 Final Conclusion

This thesis demonstrates that battery swapping is the optimal zero-emission electrification pathway for heavy-duty trucks operating in high-utilisation, geographically constrained logistics systems. However, its successful adoption depends less on further engineering advances than on the deliberate orchestration, of standards, policy frameworks, and business models.

This conclusion is grounded in a comprehensive empirical assessment combining a systematic literature review, policy analysis, case studies, expert interviews, grid-impact modelling, and multi-criteria decision analysis. Across these strands, the findings show that battery swapping delivers exceptionally low operational downtime, strong grid flexibility through decoupled charging, and favourable total cost of ownership under predictable, high-throughput operating conditions. In contexts such as ports, mines, regional industrial corridors, and depot-based fleet operations, battery swapping can outperform both megawatt charging and hydrogen fuel-cell solutions on key operational and system-level criteria.

At the same time, the analysis demonstrates that the uneven global deployment of battery swapping cannot be explained by technological feasibility alone. The Multi-Level Perspective (MLP) analysis reveals that adoption outcomes are shaped primarily by the alignment, or misalignment of landscape pressures, regime structures, and niche conditions. China illustrates that when industrial strategy, policy direction, OEM coordination, and logistics characteristics align, battery swapping can reach full commercial maturity. In contrast, Europe and North America show that in the absence of OEM standardisation, targeted policy recognition, and coordinated infrastructure planning, battery swapping remains confined to pilots or early feasibility stages despite its technical and economic merits.

The comparative analysis further confirms that technology choice in heavy-duty truck electrification is not driven solely by performance optimisation. Megawatt charging benefits from strong regime compatibility and policy endorsement, while hydrogen fuel-cell pathways are sustained by long-term strategic narratives despite weaker near-term economics. Battery swapping occupies a distinct position: technically mature and system-efficient, yet institutionally constrained. The observed mismatch between MCDA rankings and real-world adoption patterns underscores the decisive role of socio-technical lock-in rather than technical inferiority.

Taken together, the results indicate that battery swapping has not failed as a technology; rather, it has stalled in regions where socio-technical regimes remain misaligned. Its future role is therefore best understood as part of a diversified zero-emission freight ecosystem, complementing depot charging, megawatt charging, and hydrogen in use cases where high utilisation and system-level coordination can be achieved. For route-predictable, high-utilization operations, such as ports, mines, and dedicated industrial corridors, the evidence suggests that planning for battery swapping is not a speculative option but a cost- and uptime-critical infrastructure decision. Delaying such planning risks avoidable logistics downtime, higher grid reinforcement costs, and slower decarbonisation precisely in those freight segments where electrification can scale most rapidly.

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APPENDIX A

Interview Materials

A1. Interview Guide (all stakeholder groups)

General Questions (asked from all stakeholder groups)

1. From your perspective, what factors have influenced the adoption or neglect of battery swapping for heavy-duty electric trucks in your region or sector (e.g., financial incentives, regulations, infrastructure readiness)?
2. What are the main technical or operational barriers to wider implementation?
3. Do you see a long-term role for battery swapping in freight decarbonization, or do you believe other technologies are more promising?
4. How would you compare battery swapping with FC, megawatt charging, and hydrogen in terms of usability, cost, and scalability?
5. Which business models (e.g., Battery-as-a-Service) or use cases (taxis, urban delivery, mining, buses) could make battery swapping viable in the future?
6. How does battery swapping affect electricity networks or grid management, particularly at scale?
7. How mature is battery swapping for HDTs from a technical and market-readiness perspective?
8. How do you assess user acceptance and trust issues related to battery swapping?
9. What is your view on the cost structure and economic feasibility of battery swapping?
10. How do you evaluate interoperability challenges with OEMs and the evolution of battery standardisation and cross-border compatibility?

A1.1. Academia Research institutes

1. What further research or technological development is critical for advancing battery swapping adoption?
2. What technical breakthroughs would significantly improve the feasibility of battery swapping?
3. How can academic research shape industry or policy directions in this area?
4. Have you observed changes in stakeholder perception toward battery swapping over time?

A1.2. Fleet Operators / Users

1. What lessons have you learned from pilot projects? What have been the biggest technical or economic challenges during deployment?
2. How do you define or measure success in pilot deployments or policy initiatives related to battery swapping?

3. What partnerships or collaborations have been essential to advancing your technology?
4. How have end users responded to your system so far? What are your next steps or plans for scaling up?

A1.3. Industry (OEMs)

1. What motivates your organisation to invest or not invest in battery swapping technologies for HDTs?
2. Can you provide an example of a successful or unsuccessful implementation in HDTs or another sector that offers relevant lessons?
3. How do engineering constraints (battery size, weight, mounting, safety) affect the feasibility of swappable platforms?

A1.4. Policy and Regulatory Authorities

1. What collaborations currently exist, or should exist, between government agencies and industry actors to support battery swapping infrastructure development?
2. What types of additional support (policy measures, incentives, coordination) are needed to accelerate adoption?
3. What lessons have been learned from early pilot programs? How did these pilots influence subsequent planning or policy adjustments?
4. How do you measure the success of policy initiatives or pilot programs related to battery swapping? What indicators are used?
5. What regulatory or administrative barriers currently hinder deployment?

A2. Recruitment and Consent Information

All interview participants were approached through purposive sampling based on their professional relevance to HDT electrification and battery swapping technologies. Participants received an information sheet describing the study objectives, voluntary nature of participation, confidentiality, GDPR compliance, and data handling procedures.

Before each interview, verbal or written informed consent was obtained. All interviews were audio-recorded with permission, transcribed verbatim, anonymised, and stored securely on encrypted University servers. Personal identifiers were removed, and participants were informed that they could withdraw at any time without consequences.

A3. Overview of Expert Interviews Conducted in 2025

Table 6. *Overview of Expert Interviews Conducted in 2025*

No.	Code	Date (2025)	Country	Stakeholder Category	Form	Duration
1	A	July 14	Germany	Industry and OEMs	Written	-
2	B	July 30	Germany	Industry and OEMs	Online	40 m
3	C	August 11	Sweden	Fleet Operators and Users	Online	1h 25 m
4	D	August 11	Sweden	Academia and Research Institutes	Online	59 m
5	E	August 14	Germany	Industry and OEMs	Online	40 m
6	F	August 18	China	Academia and Research Institutes	Online	55 m
7	G	August 21	Sweden	Policy and Public Authorities	Online	32 m
8	H	August 25	Sweden	Academia and Research Institutes	Online	52 m

9	I	August 27	Finland	Fleet Operators and Users	Online	40 m
10	J	September 4	Sweden	Industry and OEMs	Online	32 m
11	D	September 8	Sweden	Policy and Public Authorities	Online	33 m

A4. Thematic Coding Framework

The interview transcripts were analyzed using inductive thematic analysis. The final coding structure consisted of the following major themes:

Table 7. *Key Thematic Categories Identified from Qualitative Analysis of Battery Swapping for Heavy-Duty Trucks*

Theme	Description	Example (paraphrased)
T1. Technology Maturity & TRL	Perceptions of readiness, performance, reliability of swapping systems	“It works well in controlled environments, but scaling is uncertain.”
T2. Operational Feasibility	Uptime, downtime, route integration, logistics fit	“Swap times are good, but site layout matters a lot.”
T3. Economic Viability	Costs, business models, fleet investment decisions	“BaaS makes CapEx easier but depends on utilisation.”
T4. Grid Impact & Energy Management	Load peaks, flexibility, buffer benefits, reinforcement needs	“With battery buffers you can fully avoid peak loads.”
T5. Regulatory & Policy Environment	Incentives, legal gaps, standardisation issues	“No regulation exists for cross-OEM compatibility yet.”
T6. User Acceptance	Trust, convenience, safety perceptions	“Drivers like it, but companies worry about ownership.”
T7. Standardisation & Interoperability	Technical compatibility, platform alignment	“Without OEM alignment, Europe cannot scale.”

APPENDIX B

MCDA SCORING EVIDENCE AND SWING RANGES

B1. Swing Ranges for MCDA Criteria

Table 8. *Swing Ranges for MCDA Criteria*

C1 - Operational Downtime	
Score	**Definition (Heavy-Duty Use Context)**
1	Stop time > 45 minutes
2	30-45 minutes but inconsistent availability
3	30-45 minutes (typical MCS)
4	10-15 minutes (typical H_2-refuelling)
5	< 10 minutes (commercial BSS performance)

C2 - Operational Expenditure (OpEx)	
Score	**Definition**
1	Highest OpEx; unstable or immature supply chain
2	2-3× BEV electricity cost (current hydrogen)
3	BEV electricity + swap service fee (BSS)
4	Lowest operational cost per km (MCS)
5	Not applicable for this study (no technology meets this)

C3 - Infrastructure CapEx	
Score	**Definition**
1	Very high CapEx (Hydrogen HD stations)
2	High CapEx (robotics + battery inventory in BSS)
3	Moderate (MCS stations, ~0.5-1 M€)
4	Lower CapEx than current MCS solutions (not observed for HD freight)
5	Very low infrastructure CapEx (not applicable for HD freight)

C4 - Vehicle CapEx	
Score	**Definition**
1	Highest truck cost (H_2-FC, tanks + stack)
2	Very high truck cost due to early-stage production and limited standardisation
3	High BEV cost due to large onboard batteries (MCS)
4	Lower upfront cost via battery leasing (BSS)
5	Not applicable

C5 - Grid Impact	
Score	**Definition**
1	Very large peak loads with no buffering or flexibility
2	Large peak loads with limited grid management options
3	Indirect grid impact (hydrogen electrolysis)
4	Low peaks due to buffered charging (BSS)
5	Not applicable (no zero-impact system exists)

C6 - Environmental Footprint	
Score	**Definition**
1	Fossil hydrogen supply chain
2	H_2-FC with partial renewable supply
3	High-material BEV systems with large battery packs
4	BEV lifecycle impacts with smaller average packs (BSS)
5	Not applicable

C7 - TRL / Policy / Acceptance	
Score	**Definition**
1	Very low TRL, no policy support or market activity
2	Low TRL; limited demonstrations, no formal policy backing
3	BSS in Europe; hydrogen HD; early-stage MCS
4	Strong policy/system alignment (MCS under AFIR)
5	Commercial maturity at scale (BSS in China only)

B2. Evidence Used for MCDA Scoring

Table 9. *Evidence Used for MCDA Scoring*

C1 - Operational Downtime			
Tech.	**Evidence**	**Source**	**Score**
BSS	3-5 min swap time (commercial China); ~8-10 min in early EU pilots, ≤5 min targeted	Cui et al. (2023); Interviews 1-A, 9-I	**5**
MCS	~30-45 min charging for long-haul operation (~600-800 km)	Fraunhofer ISI & P3 Group (2025)	**3**
H_2-FC	~10-15 min refuelling time	H_2.Live Consortium (2022)	**4**
C2 - Operational Expenditure (OpEx)			
Tech.	**Evidence**	**Source**	**Score**
BSS	Electricity cost + swapping service fee; partially offset by reduced downtime	Hao et al. (2025); Interview evidence	**3**
MCS	Lowest energy cost per km due to grid electricity and high drivetrain efficiency	Shen & Mao (2023)	**4**
H_2-FC	High production, compression, and distribution costs; significantly higher OpEx than BEVs	IEA (2022c); Wu et al. (2024)	**2**
C3 - Infrastructure CapEx			
Tech.	**Evidence**	**Source**	**Score**
BSS	High upfront cost from robotics, battery inventory, and grid works (≈ €1-2M per station)	Cui et al. (2023); Interview evidence	**2**
MCS	Lower site CapEx per location, but grid reinforcement often required (≈ €0.5-1M)	Bernard et al. (2022)	**3**
H_2-FC	Most capital-intensive option; high CapEx and O&M for HRS	IEA (2022c); Wu et al. (2024)	**1**
C4 - Vehicle CapEx			
Tech.	**Evidence**	**Source**	**Score**
BSS	Battery-as-a-Service allows purchase of truck body without battery, reducing upfront capital needs	Bernard et al. (2022)	**4**
MCS	Very large onboard battery packs (≈600 kWh+) increase vehicle purchase cost	Charged EVs (2023)	**3**
H_2-FC	High fuel-cell stack and high-pressure tank costs; low production volumes	Basma et al. (2022)	**2**

C5 - Grid Impact			
Tech.	**Evidence**	**Source**	**Score**
BSS	Off-peak/asynchronous charging and embedded buffer storage mitigate peak loads	Liu & Danilovic (2021); Interview evidence	**4**
MCS	1-2 MW peak load per charger without local buffers; mitigation possible via on-site storage	Bernard et al. (2022); Interviews	**2**
H_2-FC	Electricity demand shifted upstream to electrolysis; grid impact pathway-dependent	IEA (2022c)	**3**
C6 - Environmental Footprint			
Tech.	**Evidence**	**Source**	**Score**
BSS	Shared batteries enable smaller average packs, reducing material demand	Togun (2025); European Environment Agency (2018); Liu & Danilovic (2021)	**4**
MCS	BEV well-to-wheel profile but larger onboard battery packs increase material intensity	Togun (2025); European Environment Agency (2018)	**3**
H_2-FC	Fossil-based hydrogen dominates supply; limited green H_2 at scale	IEA (2022c)	**2**
C7 - TRL / Policy / Acceptance			
Tech.	**Evidence**	**Source**	**Score**
BSS	Commercially proven at scale in China (TRL 9), but limited standardisation and policy support in EU/US (TRL ~4-6)	Electrive (2021); Cui et al. (2023); ACEEE (2025); Nåbo et al. (2024); Interviews	**3**
MCS	Strong alignment with EU/US standards and AFIR deployment targets; active harmonisation	AFIR (2023); CharIN (2025)	**4**
H_2-FC	Strong policy attention, but HD truck TRL and refuelling networks still maturing	Camacho et al. (2022); Ruf et al. (2020)	**3**

Table 10. *MCDA criteria weighting and scoring by Interviewee 9-I (Fleet Operators and Users)*

Criterion	Importance score	Normalised weight	Weighted score
C1: Operational Downtime	4	0.14	0.71
C2: Operational Expenditure (OpEx)	5	0.18	0.54
C3: Infrastructure CapEx	4	0.14	0.29
C4: Vehicle CapEx	4	0.14	0.57
C5: Grid Impact	4	0.14	0.57
C6: Environmental Footprint	3	0.11	0.43
C7: TRL / Policy / Acceptance	4	0.14	0.43
Sum	28	1.00	3.54

Table 11. *MCDA criteria weighting and scoring by Interviewee 7-G (Policy and Public Authorities)*

Criterion	Importance score	Normalised weight	Weighted score
C1: Operational Downtime	5	0.19	0.93
C2: Operational Expenditure (OpEx)	4	0.15	0.44
C3: Infrastructure CapEx	3	0.11	0.22
C4: Vehicle CapEx	4	0.15	0.59
C5: Grid Impact	3	0.11	0.44
C6: Environmental Footprint	3	0.11	0.44
C7: TRL / Policy / Acceptance	5	0.19	0.56
Sum	27	1.00	3.63

Table 12. *MCDA criteria weighting and scoring by Interviewee 5-E (Industry and OEMs)*

Criterion	Importance score	Normalised weight	Weighted score
C1: Operational Downtime	3	0.14	0.68
C2: Operational Expenditure (OpEx)	4	0.18	0.55
C3: Infrastructure CapEx	3	0.14	0.27
C4: Vehicle CapEx	3	0.14	0.55
C5: Grid Impact	2	0.09	0.36
C6: Environmental Footprint	3	0.14	0.55
C7: TRL / Policy / Acceptance	4	0.18	0.55
Sum	22	1.00	3.50

Table 13. *MCDA criteria weighting and scoring by Interviewee 6-F (Academia and Research Institutes)*

Criterion	Importance score	Normalised weight	Weighted score
C1: Operational Downtime	5	0.16	0.78
C2: Operational Expenditure (OpEx)	5	0.16	0.47
C3: Infrastructure CapEx	5	0.16	0.31
C4: Vehicle CapEx	5	0.16	0.63
C5: Grid Impact	4	0.13	0.50
C6: Environmental Footprint	4	0.13	0.50
C7: TRL / Policy / Acceptance	4	0.13	0.38
Sum	32	1.00	3.56

Table 14. *Equal-weight*

Criterion	Weight	Weighted score
C1: Operational Downtime	0.14	0.71
C2: Operational Expenditure (OpEx)	0.14	0.43
C3: Infrastructure CapEx	0.14	0.29
C4: Vehicle CapEx	0.14	0.57
C5: Grid Impact	0.14	0.57
C6: Environmental Footprint	0.14	0.57
C7: TRL / Policy / Acceptance	0.14	0.43
Sum	1	3.57

Table 15. *Aggregate-mean*

Criterion	Mean importance score (interviews)	Normalised weight*	Weighted score
C1: Operational Downtime	3.40	0.13	0.64
C2: Operational Expenditure (OpEx)	4.50	0.17	0.51
C3: Infrastructure CapEx	3.75	0.14	0.28
C4: Vehicle CapEx	4.00	0.15	0.61
C5: Grid Impact	3.25	0.12	0.49
C6: Environmental Footprint	3.25	0.12	0.49
C7: TRL / Policy / Acceptance	4.25	0.16	0.48
Sum	26.40	1.00	3.51

Table 16. *Economics-oriented weighting scenario*

Criterion	Priority indicator	Normalised weight*	Weighted score
C1: Operational Downtime	0	0.00	0.00
C2: Operational Expenditure (OpEx)	1	0.33	1.00
C3: Infrastructure CapEx	1	0.33	0.67
C4: Vehicle CapEx	1	0.33	1.33
C5: Grid Impact	0	0.00	0.00
C6: Environmental Footprint	0	0.00	0.00
C7: TRL / Policy / Acceptance	0	0.00	0.00
Sum	3	1.00	3.00

Table 17. *Policy/Grid-oriented weighting scenario*

Criterion	Priority indicator	Normalised weight*	Weighted score
C1: Operational Downtime	0	0.00	0
C2: Operational Expenditure (OpEx)	0	0.00	0
C3: Infrastructure CapEx	0	0.00	0
C4: Vehicle CapEx	0	0.00	0
C5: Grid Impact	1	0.50	2
C6: Environmental Footprint	0	0.00	0
C7: TRL / Policy / Acceptance	1	0.50	1.5
Sum	2	1.00	3.5

Table 18. *Environment-oriented*

Criterion	Priority indicator	Normalised weight*	Weighted score
C1: Operational Downtime	0	0.00	0
C2: Operational Expenditure (OpEx)	0	0.00	0
C3: Infrastructure CapEx	0	0.00	0
C4: Vehicle CapEx	0	0.00	0
C5: Grid Impact	0	0.00	0
C6: Environmental Footprint	1	1.00	4
C7: TRL / Policy / Acceptance	0	0.00	0
Sum	1	1.00	4

**In tables 16-18 priority indicator denotes whether a criterion is included in the scenario. Normalised weights are assigned only to included criteria and sum to 1.00.*

Table 19. *Final MCDA scores and rankings of charging and propulsion options across interview-based and weighting scenarios*

Scenario	BSS	MCS	H_2-FC	Rank
Expert 9-I	3.536	3.179	2.429	BSS > MCS > H_2-FC
Expert 7-G	3.630	3.222	2.556	BSS > MCS > H_2-FC
Expert 5-E	3.500	3.273	2.409	BSS > MCS > H_2-FC
Expert 6-F	3.563	3.156	2.406	BSS > MCS > H_2-FC
Equal-weight	3.571	3.143	2.429	BSS > H_2-FC > MCS
Mean-weight	3.513	3.208	2.400	BSS > MCS > H_2-FC
Economic	3.000	3.333	1.667	MCS > BSS > H_2-FC
Policy/Grid	3.500	3.000	3.000	BSS > MCS = H_2-FC
Environmental	4.000	3.000	2.000	BSS > MCS > H_2-FC

Table 20. *Sensitivity analysis of MCDA results using interviewee elimination (leave-one-out) scenarios*

Scenario (Elimination)	**BSS**	**MCS**	**H_2-FC**	**Rank**
Mean w/o 9-I	3.564	3.217	2.457	**BSS > MCS > H_2**
Mean w/o 7-G	3.533	3.203	2.415	**BSS > MCS > H_2**
Mean w/o 5-E	3.576	3.186	2.463	**BSS > MCS > H_2**
Mean w/o 6-F	3.555	3.225	2.464	**BSS > MCS > H_2**

Table 21. *Mapping of Literature Review (Sections 2.2-2.10) to MCDA Criteria (C1-C7)*

MCDA Criterion	Definition (in this thesis)	Key Evidence from Chapter 2	Main Sections
C1 – Operational Downtime	Time required for energy replenishment and impact on vehicle availability	Battery swapping enables rapid energy replenishment (≈5–10 min), comparable to conventional refuelling; fast and megawatt charging typically require 30–90 minutes or longer depending on battery size; hydrogen refuelling requires ~10–15 minutes	2.2, 2.5
C2 – Operational Expenditure (OpEx)	Energy and operational costs per km, including downtime effects	Battery swapping combines electricity cost with a swap fee but reduces productivity losses from downtime; BEVs have low €/km electricity cost but are sensitive to peak tariffs; hydrogen OpEx remains significantly higher due to fuel and system costs	2.2, 2.3, 2.5
C3 – Infrastructure CapEx	Capital investment required for refuelling/charging infrastructure	Battery swapping stations require high upfront investment (~€1–1.5M per site) due to battery inventory and automation; MCS requires grid reinforcement, substations, and high-capacity connections; hydrogen stations are among the most capital-intensive; ERS requires large-scale public infrastructure	2.2, 2.3, 2.4
C4 – Vehicle CapEx	Upfront vehicle purchase cost excluding infrastructure	Large onboard batteries increase BEV truck CapEx; battery swapping enables Battery-as-a-Service (BaaS), reducing upfront vehicle cost by shifting battery ownership; hydrogen trucks have high vehicle CapEx due to fuel cell stacks and storage tanks	2.2, 2.3, 2.7
C5 – Grid Impact	Peak load, load flexibility, and system-level electricity impacts	Megawatt charging creates localized MW-scale peaks and grid stress; ERS requires continuous medium-voltage supply; battery swapping enables off-peak charging, buffering, and microgrid-like operation, reducing peak demand and improving grid flexibility	2.4, 2.5
C6 – Environmental Footprint	Lifecycle material use and GHG emissions	Large battery packs increase material demand for BEVs; battery swapping may reduce average battery capacity through shared utilisation; hydrogen lifecycle emissions depend strongly on production pathway; ERS and MCS impacts depend on electricity mix	2.2, 2.3, 2.4
C7 – TRL, Policy Alignment & Acceptance	Technological maturity, policy support, and real-world adoption	Battery swapping has reached TRL 9 in China and Australia with strong policy support; Europe and North America remain at TRL 4–6 with pilot projects; policy frameworks (e.g., AFIR, NEVI) currently favour plug-in charging over swapping	2.8, 2.9, 2.10

APPENDIX C

The grid-impact model

Table 22. *Hourly Grid Load, Charger Utilisation, and Overload Indicators for the Battery Swapping Station*

Hour	D(t)	E-battery	P-charger	N-chargers	P-aux	T-charge	P-transformer	Inventory-Start	Served-Swaps	Unmet-Swaps	Starts	Active-Chargers	Completed-Charges	Inventory-End	Load-kW	Overload	Load-kW-B	Headroom-kW	Load_B_Final
0	1	450	350	12	15	2	3000	12	1	0	0	0	0	11	15	No	15	2985	2024
1	1	450	350	12	15	2	3000	11	1	0	0	0	0	10	15	No	15	2985	2024
2	1	450	350	12	15	2	3000	10	1	0	1	1	0	9	365	No	365	2635	2139
3	1	450	350	12	15	2	3000	9	1	0	2	3	0	8	1065	No	1065	1935	2368
4	1	450	350	12	15	2	3000	8	1	0	3	5	1	8	1765	No	1765	1235	2596
5	2	450	350	12	15	2	3000	8	2	0	4	7	2	8	2465	No	2465	535	2825
6	3	450	350	12	15	2	3000	8	3	0	5	9	3	8	3165	YES	3000	0	3000
7	4	450	350	12	15	2	3000	8	4	0	6	11	4	8	3865	YES	3000	0	3000
8	5	450	350	12	15	2	3000	8	5	0	6	12	5	8	4215	YES	3000	0	3000
9	6	450	350	12	15	2	3000	8	6	0	6	12	6	8	4215	YES	3000	0	3000
10	6	450	350	12	15	2	3000	8	6	0	6	12	6	8	4215	YES	3000	0	3000
11	7	450	350	12	15	2	3000	8	7	0	6	12	6	7	4215	YES	3000	0	3000
12	8	450	350	12	15	2	3000	7	7	1	6	12	6	6	4215	YES	3000	0	3000
13	8	450	350	12	15	2	3000	6	6	2	6	12	6	6	4215	YES	3000	0	3000
14	7	450	350	12	15	2	3000	6	6	1	6	12	6	6	4215	YES	3000	0	3000
15	6	450	350	12	15	2	3000	6	6	0	6	12	6	6	4215	YES	3000	0	3000
16	6	450	350	12	15	2	3000	6	6	0	6	12	6	6	4215	YES	3000	0	3000
17	5	450	350	12	15	2	3000	6	5	0	6	12	6	7	4215	YES	3000	0	3000
18	4	450	350	12	15	2	3000	7	4	0	6	12	6	9	4215	YES	3000	0	3000
19	3	450	350	12	15	2	3000	9	3	0	4	10	6	12	3515	YES	3000	0	3000
20	3	450	350	12	15	2	3000	12	3	0	1	5	6	15	1765	No	1765	1235	2596
21	2	450	350	12	15	2	3000	15	2	0	0	1	4	17	365	No	365	2635	2139
22	2	450	350	12	15	2	3000	17	2	0	0	0	1	16	15	No	15	2985	2024
23	2	450	350	12	15	2	3000	16	2	0	0	0	0	14	15	No	15	2985	2024