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White Paper

Battery swapping for heavy-duty commercial vehicles as a complement to conductive charging

On behalf of:

DHL Group

DSV
Global Transport and Logistics

GREIWING
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44227 Dortmund
verkehrslogistik@iml.fraunhofer.de
www.iml.fraunhofer.de/verkehrslogistik

Authors
Philipp Müller M.Sc.
Dipl.-Logist. Daniela Kirsch

On behalf of (in alphabetical order)
DHL Group
DSV Holding Germany GmbH
Greiwing Truck & Trailer GmbH & Co.KG
Nagel-Group Logistics SE
REMONDIS Sustainable Services GmbH
REWE Markt GmbH

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1. Executive Summary

The present white paper evaluates battery swapping for heavy-duty vehicles (HDV) as a complementary component alongside depot charging, High Power Charging (HPC), and, prospectively, Megawatt Charging System (MCS) solutions. The analysis is prompted by increasingly stringent CO_2 fleet targets for newly registered HDVs, as well as practical constraints relating to grid connections, available space, and operational vehicle dwell times. It considers international developments, the current European landscape, stakeholder perspectives derived from practical experience, and Total Cost of Ownership (TCO) alongside broader system effects, in order to appraise the benefits, limitations, and prerequisites for a potential roll-out within Europe.

From a technological standpoint, battery swapping has matured beyond the demonstrator phase. Automated exchange processes can now be executed within a matter of minutes, with secure high voltage (HV) interfacing and digitally orchestrated operations. In China, such systems are already being deployed at scale, whereas in Europe, the landscape remains characterised by pilot initiatives and ongoing standardisation efforts. From a regulatory perspective, the European Union (EU) continues to focus primarily on Combined Charging System (CCS) and MCS infrastructures; battery swapping is, as yet, only marginally addressed. This constellation gives rise to a pressing need for ‘proof under real-world conditions’ within Europe.

Feedback from industry practice is notably consistent: depot charging remains the foundational pillar, whilst public fast charging is only gradually enabling long-haul operations. Battery swapping offers distinct value in scenarios where time-critical processes, predictable transport corridors, and constrained grid or spatial resources coincide - for instance, in hub-to-hub logistics operating across multiple shifts, or in continuous 24/7 industrial transport within factory environments. Key barriers to entry include the absence of cross-manufacturer mechanical interoperability, unresolved questions concerning ownership, liability, and metrological compliance (including the condition upon battery return), the capital lockup associated with maintaining a battery pool, and the requirements for redundancy and operational availability of swapping stations.

From an economic perspective, the viability of battery swapping is highly context-dependent. Advantages arise from markedly reduced exchange times - thereby lowering opportunity costs - alongside the potential for optimised battery ”right-sizing“ within vehicles, the implementation of Battery-as-a-Service (BaaS) models which alleviate capital lockup for users, and the provision of predictable load profiles. These benefits must, however, be weighed against the additional capital expenditure required for automated swapping stations and the associated battery pool. Notably, battery swapping stations share similarities with HPC and MCS charging points in their dependence upon utilisation rates to achieve economic viability. In high-frequency, well-structured operational contexts, such additional investments may be amortised through increased vehicle throughput, reduced spatial requirements, and enhanced scheduling predictability. Organisational complexity may be diminished in comparison with purely ad hoc charging paradigms. From a systemic standpoint, battery swapping - unlike depot charging absent stationary energy storage solutions - may contribute to the smoothing of local load peaks, the mitigation of grid connection constraints, and the potential obviation of certain stationary capacity requirements. In sum, battery swapping is not to be regarded as a substitute, but rather as a complementary mechanism and potential accelerator of electrified logistics within clearly delineated use cases.

For a robust and scalable roll-out, three principal strands are recommended:

1. Technical reference architecture (encompassing standardised swapping formats, HV interfacing, cooling systems, communication standards and protocols, transparency regarding State of Health (SoH) and State of Charge (SoC), as well as interoperability testing),
2. Compliance pathway (ensuring metrologically compliant kWh billing, clearly defined ownership and liability frameworks, and adherence to construction, fire safety, and operational regulations)
3. Operations and market organisation (including open protocols, reservation and access systems, service level agreements (SLAs), fallback mechanisms via HPC/MCS, and cross-border clearing processes).

There exists no singularly ‘perfect’ moment for implementation. Rather, it is judicious to commence with open-standard corridor pilots anchored by committed fleets, complementing the ongoing expansion of CCS and MCS infrastructures. Such initiatives should align with national strategies, such as the German Masterplan Ladeinfrastruktur 2030, in order to address technical, regulatory, and economic questions under real-world conditions, and to preclude the emergence of de facto standards imposed by non-European solutions.

2. Introduction

> »The electrification of heavy-duty vehicles must be accelerated.«

Heavy-duty vehicles (HDV) (including lorries, buses, and coaches) account for more than one quarter of greenhouse gas emissions from road transport within the EU, and for over 6 per cent of total EU emissions (European Commission, 2025). In this context, the EU CO_2 standards for newly registered HDVs were further tightened in 2024: in addition to the continuing target of a 15 % reduction by 2025, more stringent emissions reduction targets now apply – 45 % by 2030, 65 % by 2035, and 90 % by 2040 - each relative to the 2019 baseline (Regulation (EU) 2024/1610) (European Parliament & Council, 2024).

Against this backdrop, the transition in propulsion systems - and thus the electrification of transport fleets operated by logistics and mobility companies - constitutes a principal lever for achieving these strategic policy objectives. However, the electrification of HDVs presents considerably greater operational and technical challenges than that of light commercial vehicles or passenger cars. Among the principal constraints are high daily mileage, narrow operational time windows, substantial energy demand per stop, limited spatial capacity at heavily frequented logistics hubs, and the imperative of reliable planning certainty. If Germany and the EU are to attain climate neutrality by (2045 and) 2050 (respectively), and if the transport sector is to make a substantive contribution thereto, the electrification of HDVs must be accelerated notwithstanding these impediments.

Battery swapping may serve as a complementary electrification pathway for HDVs, with the potential to alleviate and partially overcome these constraints. Energy is supplied within a matter of minutes through the exchange of a pre-charged battery, rather than by charging the vehicle during extended dwell times. In this manner, idle periods may be minimised, battery parameters more precisely tailored to operational requirements, and charging processes relocated to dedicated stations, where they may be managed in a grid-supportive fashion.

The present white paper is conceived as a stimulus for a cross-sectoral discourse among users, Original Equipment Manufacturers (OEMs), grid and charging infrastructure operators, policymakers, and the research community. It integrates technological, economic, and energy-system perspectives; situates international experience and developments within the European regulatory and operational context; and ultimately formulates concrete and differentiated recommendations for action. The subsequent third chapter establishes a foundational understanding of battery swapping as a concept. It includes a definition and delineation vis-à-vis alternative charging strategies, together with an overview of the current state of play in Asia, Europe, and Germany. Existing projects and international developments are duly considered. Thereafter, these findings are examined in conjunction with practitioners and domain experts *(see Chapter 4)*, to juxtapose the potential benefits and constraints of the concept and to attribute these appropriately to the respective stakeholder groups. Building upon this, Chapter 5 reflects upon these insights with a view to identifying the principal framework conditions relevant to the introduction of battery swapping within the European market.
In this context, particular attention is given to delineating promising application domains in which battery swapping may offer advantages over cabled charging solutions. Key cost components are likewise addressed. The paper concludes with a set of cross-sectoral recommendations designed to outline possible next steps towards a broader and more structured roll-out of battery swapping solutions.

3. Technological Overview

Battery swapping denotes the (predominantly) automated exchange of depleted traction batteries for fully charged units within purpose-built stations. The interchangeable battery modules (Swappable Battery Systems (SBS)) are, for example, removed from and replaced within the vehicle either from below or from the side. Vehicles remain within the station only for the duration of the swapping procedure, together with any incidental waiting time, whilst the actual charging of the batteries may be conducted within the station environment in a manner optimised for both grid conditions and energy pricing. In this way, the temporal dependency between the charging process and vehicle operation may be reduced or indeed decoupled altogether. For heavy-duty road freight transport, this decoupling effect is of particular significance, as it enables high levels of vehicle availability whilst maintaining a manageable load on the electricity grid. This is achieved through the pre- and post-charging of batteries at comparatively moderate charging capacities.

The technological maturity of battery swapping for HDVs has now advanced well beyond the stage of mere demonstrators and pilot projects. Core functionalities - such as the mechanised removal and installation of traction batteries, secure electrical interfacing, digital identification and authorisation processes, and integrated operational and charging management - have already been implemented at an international level, including within Europe. The following sections set out the relevant international and European technological and regulatory developments in greater detail.

3.1 International Status Quo

3.1.1 International Developments

A range of international enterprises are actively engaged in the technical implementation of battery swapping for HDVs. Particularly companies headquartered in Asia have in some instances already deployed battery swapping at an industrial scale, with developments in China, most notably, gathering increasing momentum.

As early as 2021, initial pilot routes incorporating dedicated swapping corridors were established in China *(see Chapter 3.1.2)*. Since that time, the absolute number of registered swap-capable HDVs has risen markedly. In 2020, only approximately 600 such vehicles were registered in China (see Figure 1), representing around 23 % of newly registered heavy-duty New Energy Vehicles (NEVs) - a category encompassing battery-electric vehicles, plug-in hybrids, and fuel cell vehicles alike. By 2024, this figure had increased to approximately 28,700 vehicles, corresponding to a market share of around 35 % within the NEV segment (He, 2025; Wang, 2024). During the ramp-up phase leading up to 2022, battery swapping thus acted as a significant driver of growth, accounting for approximately 49 % of NEVs, within the still nascent battery-electric HDV segment. At the same time, following this peak phase, approximately one in three newly registered HDVs in China remained swap-capable as of 2024. This stabilisation of market share reflects both the broadening of the overall NEV and electric commercial vehicle portfolio, and the continued acceleration in the market diffusion of such vehicles.

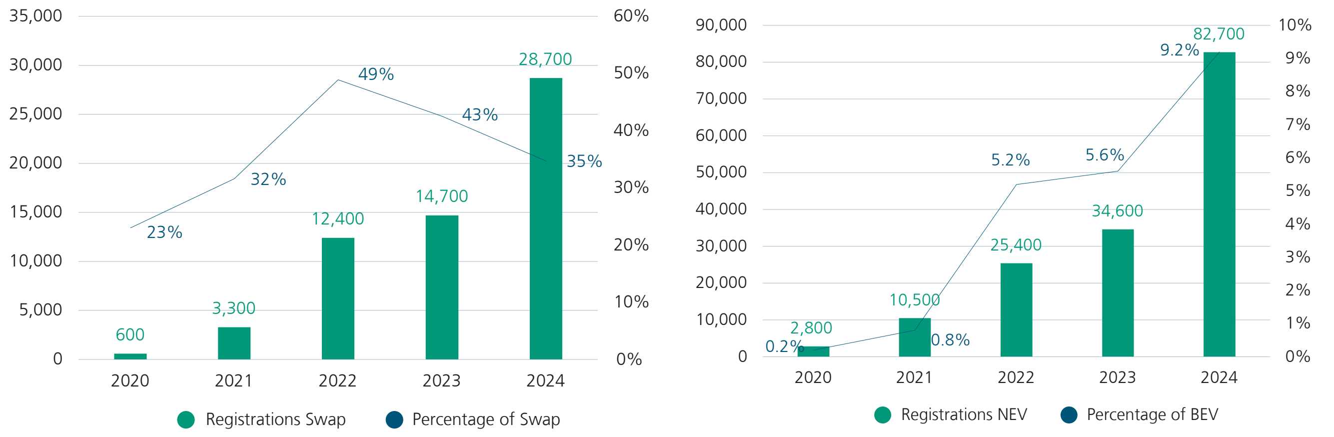

Figure 1: Number of registrations of battery-swappable HDVs, their share of NEVs in China, as well as NEV registrations and the share of BEVs in the total fleet of HDVs for the period 2021 to 2024 (He 2025; Wang 2024)

Figure 2: Battery replacement options offered by CATL (Image: CATL)

Contemporary Amperex Technology Co. Limited (CATL) is among the principal enterprises driving these developments in China. According to industry analyses, CATL dominates the Chinese market for traction batteries in battery-electric HDVs, commanding a market share of approximately 70 % (ThinkerCar, 2025). The company has advanced battery swapping for commercial vehicles along a discernible evolutionary trajectory - from rear-mounted, fully exchangeable battery enclosures ("back-swap") to underfloor, standardised battery modules ("bottom-swap") (see Figure 2). Both systems have been integrated across a wide range of Chinese commercial vehicle platforms, including tractor units, construction vehicles, and distribution lorries. Within Asia, CATL collaborates, inter alia, with BYD, Foton, and SANY (He, 2025).

In 2023, CATL introduced an integrated truck battery swapping system under the brand "QIJI", and in 2025 specified a standardised "75# Swapping Electric Block (SEB)" for heavy-duty applications (Randall, 2025). For long-haul freight transport, CATL has operated, since 2023, the first dedicated trunk-line swapping corridor for lorries between Ningde and Xiamen, spanning approximately 420 kilometres and comprising four stations (CATL, 2023). This comprehensive system encompasses, inter alia, battery swapping stations, battery packs, and a cloud-based platform. Customers may select between one, two, or three battery packs according to operational requirements. Each pack provides a capacity of 171 kWh, enabling a maximum total capacity of 513 kWh. According to company statements, each station is equipped with 24 battery packs and is capable of facilitating up to 192 swaps per day. For 2025, CATL has announced the planned deployment of 300 truck swapping stations across China. Furthermore, next-generation battery packs are expected to offer an increased capacity of 200 kWh each (He, 2025).

On both the vehicle manufacturing and operational fronts, an expansion of compatibility and platform strategies may be observed. OEMs NIO and Geely entered into a cooperation agreement in the passenger car segment at the end of 2023, focusing on standardisation, network operation, and mutual compatibility. In 2024, further agreements followed, including with Guangzhou Automobile Group, with an emphasis on shared standards, grid integration, and data interoperability. In parallel, NIO and CATL are collaborating on the development of longer-lasting battery packs for swapping systems, with the objective of maintaining high residual capacity even after prolonged operational use. This is intended to reduce lifecycle costs within BaaS business models. In 2025, Anhui Jianghuai Automobile (JAC), in cooperation with CATL, introduced a system capable of completing a battery swap within a mere 150 seconds. The partners intend to establish approximately 1,000 such swapping stations across China by the end of 2025 - of which 27 cities had already been equipped by mid-2025 - and envisage a long-term expansion to more than 10,000 stations (Hampel, 2025a). Further expansion initiatives include cooperation with the energy and fuel station operator Sinopec, aimed at achieving a substantial densification of swapping locations nationwide (CATL, 2025).

Geely, another Chinese automotive group and a cooperation partner of CATL, is likewise presenting battery swapping stations for HDVs and is targeting construction vehicles (including concrete mixers) with one of its systems. In these commercial vehicles, the interchangeable battery system is housed as a self-contained unit behind the driver's cab ("back-swap"). Rather than an underfloor exchange, a gantry crane

Figure 3: Operation of a swapping station for concrete mixers (Image: Geely)

automatically lifts out the battery block, weighing approximately 3.2 tonnes, and replaces it with a fully charged unit. According to Geely, the entire swapping process takes around five minutes and is initiated by scanning a QR code that the driver must present; the system also incorporates wheel guidance for precise positioning *(see Figure 3)*. Geely states the battery capacity to be 280 kWh, enabling the vehicles to achieve a range of approximately 190 km while simultaneously supplying power to auxiliary systems. The stations are of modular design and can optionally be equipped with rooftop photovoltaic components. They typically stock eight battery packs, recharge them from 0 to 100 % in around one hour, and are thus capable of servicing "up to 50 vehicles" (Geely, 2022).

Battery swapping is also being trialled and, in some cases, already deployed operationally in other countries: In Japan, a joint venture between Mitsubishi Fuso and the US-based swapping provider Ample has been piloting battery swapping for distribution lorries in Tokyo since 2023. From 2025, the concept is being expanded into a network of stations across Tokyo, initially focused on fleet operations. Trials in Kyoto with Yamato Transport demonstrate the suitability of the approach for courier and delivery use cases under real-world road conditions (Hampel 2025b; Westerheide 2024; Hampel 2023a). The Australian manufacturer Janus Electric is equipping lorries with interchangeable battery systems, achieving ranges of between 400 and 600 km (Hampel 2021). In addition, large-scale fleet applications have emerged within a short period of time in Southeast Asia.

In 2025, Thailand announced the introduction of 4,200 swap-capable electric lorries. At the same time, U Power opened Southeast Asia's first fully automated "smart" swapping station in Phuket and agreed a partnership with Beijing Foton to collaborate on battery swapping for HDVs in markets both within and beyond Southeast Asia (Parikh 2025a). In India, the first swap-capable heavy-duty electric fleet entered operation in 2025 at Jawaharlal Nehru Port Trust in Mumbai, with a focus on short swapping times to ensure high vehicle availability (Parikh 2025b). In this context, plans envisage the addition of 4,500 swap-capable vehicles to the fleet and the construction of 60 swapping stations by 2028 (He 2025).

3.1.2 Regulation

International regulatory and standardisation activities are being driven to a significant extent by China. Since the early 2020s, the Chinese government has been systematically embedding battery swapping within its industrial and infrastructure policy, combining strategic direction, pilot funding, standardisation, and pricing/tariff rules into a coherent system of incentives. The starting point is the Development Plan for the New Energy Vehicle (NEV) Industry (2021–2035), which schedules the expansion of charging and swapping infrastructure, the standardisation and harmonisation of connector systems, interfaces and communication protocols, as well as their integration into intelligent energy and data platforms. Among other measures, the plan calls for improvements in swapping convenience within the first five years and for the establishment of a framework for standardisation and safety. At the same time, no numerical targets have been set for the expansion of swapping stations (ICCT 2021). Nevertheless, these provisions create planning and investment certainty for downstream departmental policies and standardisation efforts.

In this context, the Chinese government initially designated eleven pilot cities in 2021, three of which were specifically focused on HDVs, and set itself the objective of supporting more than 100,000 swap-capable vehicles and over 1,000 stations within these pilot schemes. A wide range of support programmes has been implemented, including subsidies of 300 CNY/kWh for the purchase of electric lorries with swappable batteries in Sichuan, as well as grants of 1 million CNY per new swapping station in cities such as Beijing and Shanghai (Wang 2024; Zhu 2022).

In parallel, a comprehensive body of standards has been established. By 2022, nearly 50 standards relating to battery swapping had been adopted in China. These include national standards for communication protocols of swappable batteries (GB/T 32895-2016, updated in 2025 to GB/T 32895-2025), interpretative guidelines for swapping stations (GB/T 51077-2015, updated in 2025 to GB/T 51077-2024), and safety requirements (NB/T 10903-2021). At the provincial level, additional technical specifications have been issued specifically for battery swapping in the heavy-duty segment, including standard dimensions for lorry batteries and interface compatibility (for example, in Hebei and Jiangsu in 2022) (Wang 2024). As outlined in Section 3.1.1, this state support has had a tangible impact, contributing to an acceleration in market dynamics.

At the corporate level, large-scale joint ventures and partnerships established through cross-OEM cooperation agreements provide the industrial framework for standardisation processes and the strengthening of roll-out activities. As early as 2022, a joint venture between SAIC, CATL, Sinopec and CNPC was formed to develop battery swapping stations, while the agreement between CATL and Sinopec, reaffirmed in 2025, envisages the expansion of a combined passenger car and lorry network (Hampel 2022; CATL 2025). Such agreements bring together the capabilities of vehicle manufacturers as well

Figure 4: Examples of international developments in the field of battery swapping for HDVs (Image: Rio Tinto, Huawei, Montra Electric, Mitsubishi) (clockwise)

as cell and system suppliers. This facilitates not only the definition of standards on the vehicle side but also the development of suitable sites, while simultaneously supporting BaaS business models. In this way, the capital expenditure (CAPEX) associated with traction batteries can be decoupled from the vehicle for end users. Agreements by NIO with Geely (2023) and Guangzhou Automobile Group (GAC) (2024) address joint battery standards, vehicle compatibility, and network interconnectivity, including dynamic data integration. Such models promote network opening and economies of scale. For Europe, the transfer of the Chinese business model is already the subject of concrete discussions and is being actively advanced by CATL, which holds the largest market share (around 70 %) in traction batteries for HDVs in the Chinese market (ThinkerCar 2025). Complementing this, a - albeit still limited - reference network by NIO already exists in several EU countries (Westerheide 2025; Randall 2024; Hampel 2023b).

Outside China, there are, to date, hardly any specific regulatory frameworks in place. In Japan and Australia, battery swapping projects are typically carried out within the scope of private-sector collaborations, without any particular legislative privileges. North America has thus far placed greater emphasis on conductive charging infrastructure; battery swapping is not explicitly addressed in funding programmes or charging standards in this region (Nåbo et al. 2024). However, the International Electrotechnical Commission (IEC) is currently advancing international standardisation efforts, including IEC 62840-1:2025 (Electric vehicle battery swap system – Part 1: General and guidance) and IEC 62840-2:2025 (Electric vehicle battery swap system – Part 2: Safety requirements). These standards provide both a general framework and detailed safety requirements for battery swapping systems in battery-electric vehicles (IEC 2025a; IEC 2025b).

3.2 Status Quo in Europe and Germany

In recent years, a range of activities has emerged across Europe, particularly in the areas of pilot deployment and technical testing, relating to battery swapping for HDVs, which are outlined below.

3.2.1 Practice

In comparison with international developments, some of which have already reached industrial scale *(see Section 3.1.1)*, activities in Germany and across Europe are primarily situated within the domain of research projects and prototype development. Within this context, Germany ranks among the most active countries in Europe in the field of battery swapping for HDVs. Between 2016 and 2020, the RouteCharge research project was funded by the Federal Ministry for Economic Affairs and Energy. As part of this project, the logistics company Meyer & Meyer, together with Fraunhofer IPK, TU Berlin, and additional partners, tested a swap-capable 19-tonne battery-electric lorry. This vehicle operated along a route of approximately 500 km between Peine and Berlin, exchanging two battery modules of 2,000 kg each at three swapping stations. At around 30 minutes, the swapping time, carried out by a trained driver using a forklift, remained significantly higher than the performance levels achieved by today's automated swapping stations (RouteCharge Consortium 2020).

Building on the RouteCharge project, which relied on manually assisted swapping, the latest findings from the eHaul project demonstrate that fully automated swapping is technically feasible from an infrastructural, operational, and safety perspective. Two articulated tractor units with a gross combination weight of 42 tonnes, based on vehicles from Designwerk, have been deployed within the Berlin-Brandenburg area and as far as Dresden. These vehicles utilised a fully automated swapping station near Berlin, which entered operation in November 2023 *(see Figure 5)*, achieving swapping times of between eight and ten minutes. The standards and operational processes developed in this context are intended to be scaled up and rolled out more broadly in the future (Jerratsch et al. 2025; Fraunhofer IVI 2024). Additionally, the research project UniSwapHD (Unified Swappable Battery for Heavy-Duty Commercial Vehicles), led by TU Berlin, is pursuing the development of a standardisation concept for swappable traction batteries (TU Berlin 2025). Emerging from these projects, E-Haul GmbH was founded in 2024 (E-Haul GmbH 2025). In addition, IBAR Systemtechnik GmbH, a project partner based in Brandenburg, is also initiating early activities in the field of battery swapping and plans to spin off AkkuSwap GmbH in 2025 (AkkuSwap powered by IBAR Systemtechnik GmbH 2025). Both companies aim to further develop the ecosystem of battery swapping stations for HDVs.

Figure 5: Battery swapping station from the e-Haul project and a prototype of the swapping module for trailers by Trailer Dynamics (Image: TU Berlin, Sustainable Truck&Van)

In parallel, Trailer Dynamics GmbH, DB Schenker and CATL have launched an initiative to introduce battery swapping technology for electric trailers in Europe. At its core is a feasibility study on the deployment of battery swapping stations intended to meet the demand for electrified trailers, and potentially lorries, across Europe. This industrial collaboration aims to improve the efficiency and economic viability of battery charging in heavy-duty transport by enabling rapid battery exchange, thereby increasing the range and operational uptime of electric vehicles. With a swapping time of around five minutes and the option to select different battery modules depending on operational requirements, the system promises higher vehicle availability, improved operational efficiency, and reduced dependence on conventional charging infrastructure. To this end, a prototype electric trailer equipped with a swappable battery system has been developed and was presented at IAA Transportation 2024 *(see Figure 5)* (Deutsche Bahn AG 2024).

The Swiss company Designwerk Technologies, today part of the Volvo Group, has likewise advanced developments in the field of battery swapping. The company offers modular, swappable traction batteries. Within the eHaul project, the vehicle–battery interface was automated in collaboration with TU Berlin, enabling battery exchange to be carried out automatically within a matter of minutes when using a suitably equipped vehicle. Designwerk regards battery swapping as a strategic complement to the MCS, particularly for fleets operating on defined route profiles (Designwerk 2025).

In United Kingdom, the Glasgow-based start-up Tual Technology presented a modular swappable battery system for HDVs in 2024. The "PowerBank Pro" modules (120 and 180 kWh, respectively) are designed to enable automated swapping within a matter of minutes. According to the company, the system is positioned as an alternative to the still emerging MCS network (Reichel 2024).

3.2.2 Regulation

Within EU funding programmes and regulatory frameworks, such as the Alternative Fuels Infrastructure Regulation (AFIR), battery swapping has so far been only marginally addressed, and no clear policy framework for its deployment within the EU has been established. The primary focus lies on the expansion of standardised charging infrastructure for battery-electric HDVs: in the short to medium term via the CCS, and, in the longer term, through the MCS for particularly high charging capacities. These regulatory measures are complemented by depot-based charging solutions and the parallel advancement of hydrogen refuelling infrastructure. For public fast charging, a coexistence of CCS and MCS is anticipated, with MCS likely to assume a central role over the longer term (European Parliament & Council 2023a).

At the technical level, however, this gap is increasingly being addressed through initial standardisation activities. A prospective consortium standard is currently under development in the form of the planned DIN SPEC "Battery swapping systems for electric heavy duty vehicles for range extension", based on the findings of the UniSwapHD research project conducted by TU Berlin. This specification is intended to define interfaces and key framework parameters for battery swapping systems in HDVs, without, however, establishing legally binding requirements (DIN 2025).

In the Master Plan Charging Infrastructure 2030 of the Federal Ministry of Transport (BMV), the "testing of battery swapping systems for electric lorries" is defined as a measure at the level of the Federal Republic. The measures set out in the plan are intended to "(…) improve the framework conditions for the development of charging infrastructure and enable consumers to use electric vehicles conveniently" (BMV 2025, p. 7).

4. Reflection with Industry Stakeholder

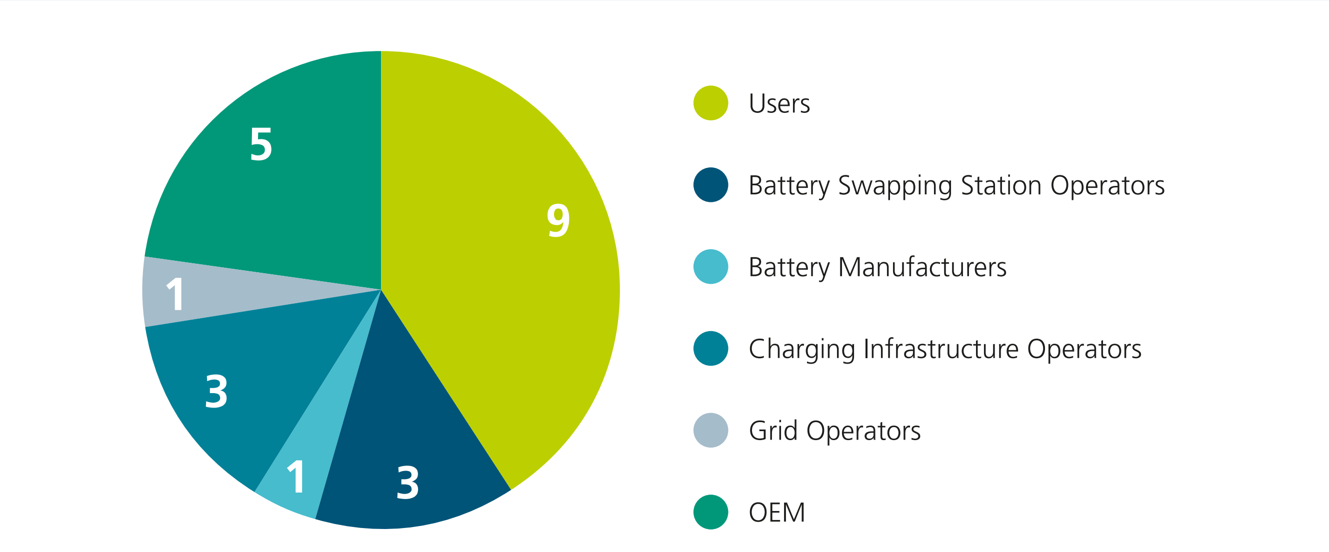

Figure 6: Expert interviews grouped by stakeholder group (total: 22)

As part of this white paper, expert interviews were conducted with a range of companies regarding the deployment of heavy battery-electric commercial vehicles. The objective was to capture the perspectives of different stakeholders on the electrification of HDV fleets and the potential role of battery swapping, particularly in the context of Europe and Germany. This chapter consolidates the findings from these discussions and presents them in a neutral manner, structured by stakeholder groups[1].

4.1 Users

Logistics companies largely assess battery swapping as a complementary option to depot-based and public HPC/MCS charging, offering clear advantages in predictable corridors and multi-shift operations. The principal benefit is seen in significantly reduced downtime through rapid swapping processes, as well as in the decoupling of energy intake from route planning. This is particularly relevant in situations where depot infrastructure, available space, and medium-voltage grid connections become limiting factors. At the same time, depot charging remains the operational cornerstone. However, as the ramp-up of heavy-duty electric vehicles progresses, capacity and space constraints are increasingly becoming key drivers for supplementary charging concepts at logistical nodes, to enable higher vehicle throughput.

From an operational perspective, five (potential) advantages are most frequently cited:

- Short swapping times (five to ten minutes in project experience), which decouple charging time from the transport operation and allow better alignment of energy intake with drivers' hours and rest regulations.
- Greater flexibility in the event of operational disruptions, such as traffic congestion, diversions or vehicle faults, as a five-minute battery swap can be integrated into existing charging schedules more easily than a one-hour charging process.

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[1] The expert discussions focused on the use of battery-electric HDVs. Other fuel sources, such as HVO 100 or Bio-LNG, were not the focus of the expert discussions.

- More balanced grid utilisation, as batteries can be charged off-vehicle in a controlled and cost-optimised manner.
- Reduced space requirements and peak load demand at the site compared with large HPC installations.
- Potential financing advantages, depending on the business model, through pay-per-use structures and reduced risk exposure, as the operator is no longer the "owner" of the battery. This lowers capital intensity, given that a substantial share of the cost of a battery-electric lorry is attributable to the battery.

These aspects are explicitly linked to the expectation that vehicles must be both swap-capable and able to charge via conventional conductive systems. At the same time, clearly defined SLAs and booking options with operators of swapping stations would be required to ensure the availability of sufficient energy capacity.

Many of the companies interviewed therefore anticipate a structural mix of depot charging, semi-public solutions, and - depending on the region - public charging offerings, which, however, appear viable only where energy prices are competitive and access routes are short. Against this backdrop, battery swapping is gaining attractiveness as a complementary option that has the potential to enable higher vehicle throughput. This view is further reinforced by the structure of the logistics sector, where the share of subcontractors is often high and not every transport company is able to establish its own medium-voltage grid connection. Overall, battery swapping is not regarded as a substitute for conductive charging, but rather as a credible component for alleviating grid, space, and time constraints during the ramp-up phase, if issues relating to standardisation, operator roles, billing models, and availability are effectively addressed.

4.2 Battery Swapping Station Operators and Battery Manufacturers

The three operators of battery swapping stations and battery manufacturers interviewed likewise regard battery swapping as a complementary component alongside depot-based and public HPC/MCS charging. From their perspective, the approach is particularly effective in contexts where routes, or specific route segments, with high vehicle frequencies coincide with tight time windows. Primary application areas are seen in multi-shift and line-haul operations characterised by high vehicle utilisation over time. The core operational benefit lies in significantly reduced vehicle downtime through automated swapping processes, currently in the range of approximately six to ten minutes. This is complemented by the decoupling of energy intake from route planning and by more balanced load profiles, as batteries can be pre- and post-charged outside vehicle operation at moderate power levels.

From an operator's perspective, battery swapping offers not only a temporal advantage but also scalability benefits for infrastructure. As utilisation increases, throughput and availability can be precisely managed via slot allocation, booking systems, and digital platforms. At the same time, continuous pre-charging reduces the required grid connection capacity and facilitates deployment at sites with limited network availability. Modular designs and battery rack systems enable compact use of space, demand-oriented battery handling, and the gradual scaling of capacity in line with operational needs.

At the same time, operators, like all other stakeholders, articulate clear conditions for successful market diffusion. Without cross-manufacturer interoperability (in terms of battery module geometry and locking mechanisms, HV and cooling interfaces, as well as communication protocols), there is a risk of isolated solutions, limited scalability, and increased inventory and liability risks. A viable operator and BaaS model must clearly define ownership, liability, insurance, as well as parameters such as State of Health (SoH) and State of Charge (SoC), including pathways for second-life use. A further prerequisite is metrologically compliant billing on a per-kWh basis for each swapping process, particularly in open-access usage scenarios.

Battery manufacturers generally consider battery swapping technology to be mature; however, in the European context they identify primarily market-specific organisational barriers. Reluctance on the part of vehicle manufacturers to adopt standardised batteries, a more stringent regulatory environment than, for example, in China, and a lack of investment incentives are seen as key factors inhibiting market diffusion. Developments in Asia are frequently used as a point of reference, although stakeholders emphasise that the underlying conditions cannot be transferred uncritically to Europe. At the same time, several voices among swapping station operators and battery manufacturers warn of a potential "glass ceiling" in achieving fleet electrification and decarbonisation targets in the European market if the sector relies exclusively on conductive charging solutions.

4.3 Grid and Charging Infrastructure Operators

Grid Operators

The grid operator interviewed anticipates a significant ramp-up of electric commercial vehicles in the heavy-duty segment, with prioritised infrastructure expansion along motorways. Depot charging, particularly when combined with on-site photovoltaic generation, is regarded as a highly cost-effective option. Dynamic approaches such as overhead line charging are considered of secondary importance following (accompanied) pilot phases. The grid operator interviewed anticipates a significant ramp-up of electric commercial vehicles in the

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heavy-duty segment, with prioritised infrastructure expansion along motorways.

For this reason, battery swapping is being monitored with a degree of technical and operational reservation but is fundamentally regarded as a user-side decision. From the perspective of grid operators, swapping can reduce power requirements at individual sites and smooth load profiles by enabling batteries to be charged outside vehicle operation at lower power levels. This may also facilitate the integration of renewable energy inputs and enable earlier commissioning of infrastructure and corresponding electrified fleets. At the same time, no substantial relief for the overall energy system is expected, as grid expansion will remain necessary and the reliability of processes and load profiles can only be demonstrated through operational experience with battery swapping at scale. The choice between conductive charging and battery swapping is ultimately seen as a matter for operators and users, while issues relating to parking space and land use fall outside the remit of grid operators - though they are recognised as important factors motivating users to engage with the topic of battery swapping.

Charging Infrastructure Operators

Charging infrastructure operators firmly position battery-electric lorries within their expansion strategies. In line with the views of other stakeholders, depot charging forms the operational backbone, while high-performance public fast charging via HPC and MCS is regarded as essential for long-distance operations. In this context, additional batteries serve as a buffer, where necessary, to bridge limited grid connection capacities and to reduce peak power costs.

Battery swapping is largely regarded as a potential complementary option that primarily offers time-related advantages, decouples charging from driving time, and enables moderate grid connection capacities as well as more predictable energy procurement through more even load profiles. At the same time, operators point to substantial entry requirements: without cross-manufacturer standardisation (mechanical design, HV and cooling interfaces, and communication), as well as clear ownership, liability, and inventory models (e.g. battery pooling/BaaS), large-scale deployment would entail considerable risk. In addition, the mechanical complexity of swapping stations introduces potential single points of failure, which would only be economically viable if mitigated through redundancy and fallback solutions. Overall, conductive charging is widely viewed as the more robust pathway, not least due to increasing charging capacities, a growing density of sites, and more mature operational processes. In parallel, shared charging parks are gaining attention as a means of increasing utilisation rates and improving total cost of ownership (TCO).

4.4 Original Equipment Manufacturers (OEMs)

The vehicle and trailer manufacturers interviewed place battery-electric lorries firmly at the centre of their strategies for the decarbonisation of commercial vehicle fleets. Depot charging is regarded as the foundational pillar, while high-power public fast charging is intended to ensure long-distance capability. A frequently cited operational model assumes vehicle ranges of around 500 kilometres, combined with a 45-minute charging stop during mandatory breaks. Dynamic charging systems, such as overhead line solutions or inductive charging, are, by contrast, largely considered unrealistic or of significantly lower priority within the EU, owing to costs, implementation timelines, and the lack of standardisation. This fundamental perspective also shapes the assessment of battery swapping: the approach is recognised as technically feasible and effective in specific use cases, particularly due to short swapping times of currently around five minutes, the decoupling of energy intake from route planning, and the possibility of separating vehicle and battery ownership on the balance sheet, thereby consolidating obsolescence risks with the operators of swapping stations.

At the same time, manufacturers point out that a cross-manufacturer swapping and interface standard is currently lacking and unlikely to emerge in the short term, constituting the principal barrier to market entry in Europe. From today's perspective, a uniform underfloor or modular format would undermine manufacturer-specific optimisation of battery integration. In addition, reservations persist regarding the long-term reliability of mechanical and electrical interfaces under conditions of daily swapping cycles. Nevertheless, several OEMs are actively involved in standardisation processes within relevant committees, such as the DIN SPEC "Battery swapping systems in electric heavy-duty vehicles – General requirements for automated battery swapping stations" (DIN 2025). From an economic standpoint, manufacturers emphasise the need for a significantly higher battery inventory (estimated at an additional 25 to 50 %) with corresponding implications for capital requirements and environmental footprint. At the same time, a parallel infrastructure for conductive charging would still need to be established and operated. Against this backdrop, a number of manufacturers take the view that battery swapping may lag behind the ongoing roll-out of the MCS in terms of timing, and that it does not offer a general advantage in terms of TCO compared with conductive charging, at least at present. They also point to ongoing advances in battery technology, leading to increased vehicle ranges and reduced charging times.

A further aspect highlighted is that, in the medium to long term, a stronger functional integration of tractor unit and trailer is conceivable, whereby both components are treated as a single system, allowing energy-related synergies to be more effectively realised. At the same time, developments in China are being closely monitored. The standard-setting influence of individual cell and system suppliers there is seen as a potential external impulse that could also gain relevance for Europe. Overall, several OEMs and component manufacturers signal their willingness to participate in working groups and standardisation initiatives. A key precondition for the viability of battery swapping is identified as the establishment of a European cross-OEM standard covering geometry, HV and cooling interfaces, and communication protocols. This must be complemented by a robust operator and BaaS model, including clearly defined ownership and liability structures as well as metrologically compliant kWh-based billing, alongside field validation demonstrating high availability without significant drawbacks in payload capacity or vehicle range.

4.5 Cross-Stakeholder Perspectives

Fleet electrification is strategically anchored across all relevant stakeholder groups. As outlined, assessments of battery swapping differ in part between these groups. At the same time, a broadly consistent picture emerges in comparison with other studies examining the acceptance of battery swapping (cf. Noto & Mostofi 2023). Within the HDV segment, companies with practical experience of electric vehicles are increasingly shifting their focus from pilot projects and isolated applications towards the scaling of fleets and the corresponding infrastructure required. Depot charging is consistently regarded as the foundational pillar and, particularly when combined with on-site photovoltaic generation as the most cost-effective option. However, the scalability of depot charging is constrained by limited medium-voltage grid connection capacities, the availability of space at operating depots, and (anticipated) growth in vehicle numbers. Stationary battery storage systems can help bridge connection gaps, smooth peak loads, and reduce power-related charges. Their economic benefit, however, varies significantly depending on the specific use case and may be associated with efficiency losses (such as those arising from power conversion) of up to 20 % (Koltermann et al. 2024).

There is broad agreement on the importance of public fast charging infrastructure based on HPC and, prospectively, MCS. It is acknowledged that the expansion of infrastructure, both public and private, is progressing. However, significant challenges remain, including very high power requirements, the availability of suitable parking spaces, the reliable availability and reservability of charging points, and the duration of permitting procedures. These issues are compounded, not least, by the fragmentation of the electricity market, which in Germany alone comprises more than 860 distribution system operators.

Battery swapping is assessed by several stakeholder groups as offering clear operational advantages. These include swapping times of around five minutes, the decoupling of charging time from route planning, lower grid connection requirements combined with potentially higher throughput, reduced space requirements, and potential benefits in terms of battery lifecycle management and second-life utilisation. However, these advantages are offset by several key barriers. Particularly, these relate to the absence of interoperable standards at both battery and interface level, the risk of manufacturer lock-in, unresolved questions regarding ownership, liability and metrological compliance, regulatory approval requirements, the capital tied up in additional battery inventories, and operational risks associated with the failure of individual stations. In international comparison, experts consistently point to China, where battery swapping has achieved a higher pace of implementation, driven by standardisation initiatives, strong governmental coordination and greater market momentum. Europe, by contrast, is lagging behind, primarily due to unresolved issues relating to standardisation, regulation, and market acceptance. This may ultimately create a risk of having to adopt external, particularly Chinese, standards.

5. Potentials and TCO

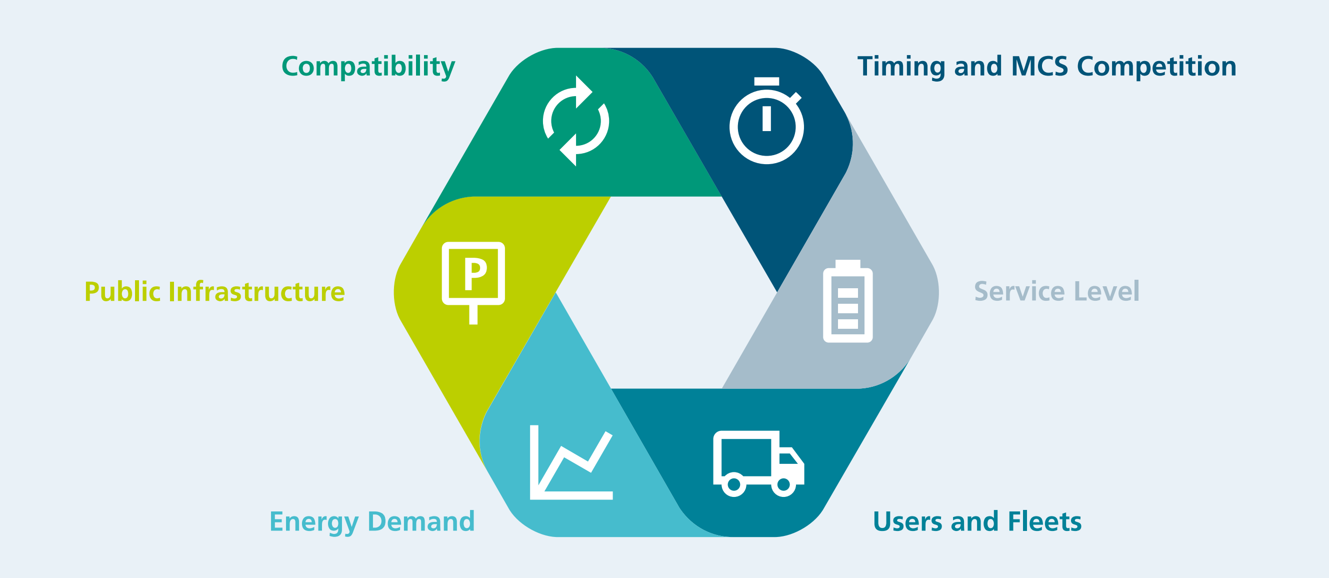

Figure 7: Consolidated potentials and barriers of battery swapping based on the expert discussions

5.1 Barriers and Potentials

Compatibility

The lack of compatibility between electric vehicle models and battery packs represents one of the most significant challenges for battery swapping in Europe. A common standard for batteries is of fundamental importance to establish a comprehensive swapping infrastructure. One potential solution could lie in the development of a uniform battery design that can be used across different vehicle platforms. However, this would require close collaboration between vehicle manufacturers, battery producers and other stakeholders. Initial steps towards standardisation are currently being taken on a selective basis and are being supported by manufacturers within standardisation bodies (DIN 2025). Nevertheless, a coordinated initiative at the European level is still lacking. Closer cooperation in the development of standards is therefore essential for scaling battery swapping technology. A look towards Asia shows that standardisation processes have already been initiated internationally and are being applied across stakeholders in practical battery swapping deployments *(see Section 3.1).*

Public Infrastructure

From a policy and regulatory perspective, battery swapping continues to play a subordinate role across the EU. The AFIR establishes an extensive network of binding charging targets (CCS/MCS) for HDVs but refers to battery swapping only as a potential future charging option, once technically feasible, without setting concrete deployment targets or support schemes (European Parliament & Council 2023a). Under the initiative “Power to the Road”, Germany is advancing the development of a lorry fast-charging network with around 350 sites in line with AFIR (NOW GmbH 2025), which may support the uptake of battery-electric vehicles during the ramp-up phase, if pricing conditions are favourable. In addition, according to the National Centre for Charging Infrastructure (as of 2 March 2026), there are currently 69 publicly accessible lorry charging sites with a total installed charging capacity of 50,160 kW. This compares with a target of 2,842,950 kVA of planned grid connection capacity. To date, therefore, around 20 % of the planned number of sites has been realised (69 out of 351), while the currently recorded installed charging capacity represents only approximately 1.8 % of the planned connection capacity for the target year 2030 (50,160 kW vs. 2,842,950 kVA) (National Centre for Charging Infrastructure 2026; NOW GmbH 2024).

Energy Demand

The electrification of heavy-duty freight transport is accompanied by a substantial increase in the electricity demand of the logistics sector. According to consistent findings across multiple studies, the additional annual electricity demand resulting from the full deployment of battery-electric HDVs in Germany is estimated to exceed 100 Terawatt-hours (TWh) by 2045 (German Council of Economic Experts (SVR) 2025; Göckeler et al. 2023). Compared with the total electricity consumption of 464.4 TWh recorded in Germany in 2024 (Federal Network Agency 2025a), this represents an increase of more than 20 %. In this context, the simultaneity of charging processes and the local grid situation play a decisive role in determining the extent to which medium- and low-voltage networks will be able to accommodate rising demand in the future. Options for energy management through the temporal shifting of charging processes are generally limited, i.a. due to defined cut-off times or multi-shift operations, since charging must be completed within designated breaks, and capital-intensive fast-charging points must not be blocked by non-charging vehicles if infrastructure utilisation is to remain efficient. Otherwise, this may necessitate (in some cases significant) adjustments to route planning to account for charging schedules and energy management constraints. Battery swapping can help to reduce vehicle downtime and increase the operational flexibility of commercial vehicle fleets (Li et al. 2024). By enabling centralised charging of batteries decoupled from vehicle operation, it can mitigate grid stress by reducing the simultaneity of high-power charging processes and can improve the integration of renewable energy sources. Vallera et al. (2021) further highlight the potential of battery swapping to support long-term grid stability while the degree of penetration by electric commercial vehicles, and the associated overall energy demand, continues to rise.

Users and Fleet Operators

Beyond the system-wide perspective, the electrification of vehicle fleets compels transport companies to fundamentally review and, where necessary, rethink, their processes and business models. As the degree of penetration by heavy-duty electric commercial vehicles increases, road freight transport is set to become one of the most energy-intensive sectors. In this context, logistics companies are no longer solely responsible for their core function – transport - but must increasingly take on energy management tasks as well, both internally and in consideration of the decisions made by other market participants and competitors. This can constitute a barrier during the ramp-up phase, particularly where energy demand is submitted to distribution system operators without coordination among stakeholders, and available capacities at the medium-voltage level are already constrained.

It should also be borne in mind that small and medium-sized enterprises (SMEs), as well as subcontractors, constitute a substantial share of the transport sector. On average across Europe, transport companies employ only around six people (European Commission: Directorate-General for Mobility and Transport 2025). As a result, their capacity to invest in and develop proprietary charging infrastructure is often limited. Battery swapping can facilitate the electrification of such fleets by potentially reducing operational risks and capital expenditure (CAPEX). At the same time, it may help to smooth overall energy demand despite even at higher levels of fleet electrification which, in turn, can provide benefits for the wider electricity system (Vallera et al. 2021).

Service Level

A further potential risk highlighted in several expert interviews concerns the SoC and SoH of swapped traction batteries. Reliable operation therefore requires clearly defined SLAs covering system availability, swapping times and error rates, as well as transparency regarding the SoC/SoH of exchanged batteries. From an operational standpoint, this necessitates a digital platform that integrates reservation systems, access management, billing and battery condition data, while also enabling the auditability of SLA compliance. Redundancy measures, including at least one fallback option via HPC/MCS charging at the site, can help mitigate single points of failure. In addition, the EU Battery Regulation supports the contractual definition of quality criteria: Article 14 mandates the provision of information on SoH and expected lifetime, whereas applicable from 2027, Article 77 requires the introduction of a Battery Passport for batteries with a capacity exceeding 2 kWh. This standardised data framework is expected to facilitate transparency regarding SoH/SoC, as well as complaint handling and quality assurance processes within battery swapping operations (European Parliament & Council 2023b).

A shared business model in which investment in the vehicle and the battery is separated offers greater flexibility, reduces CAPEX for the user, and can extend the service life of individual components, namely both the vehicle and the batteries. Battery swapping can contribute to a longer battery lifespan. Batteries charged within a swapping system can be managed under controlled grid-charging conditions, which may require lower peak power and allow for more optimised charging strategies, thereby supporting durability. Batteries that are not immediately in circulation can be maintained within a narrow state-of-charge window, reducing calendar ageing. Moreover, the decoupling of battery and vehicle lifecycles creates favourable conditions for standardised reuse and efficient recycling. This aligns with the objectives of the EU Battery Regulation (EU) 2023/1542 in promoting a circular economy (ibid.).

Timing and Competition with MCS

Some experts express scepticism and point to timing risks, the lack of standardisation, and potential trade-offs in packaging, range, and payload when compared with the ongoing ramp-up of the MCS. At the same time, however, all stakeholders involved are, through their activities, building up relevant expertise and potential synergies for a future battery swapping system, for example through slot and booking concepts, open-standard platforms, and medium- and high-voltage grid integration. From an industry perspective in Europe, the strategic pathway is currently shaped by HPC and MCS. Organisations such as CharIN and SAE International are advancing MCS rapidly (up to 3,000 A / 1,250 V), thereby increasing the availability of high-performance charging hubs. The Megawatt Charging System (MCS) Technical Information Report SAE J3271, published in 2025, outlines system requirements ranging from grid connection to communication protocols (SAE 2025). These developments do not necessarily diminish the relevance of battery swapping, particularly as MCS charging further increases demands on grid connections. Rather, the available evidence suggests the need to differentiate between use cases: where highly predictable operations, homogeneous fleets and high-frequency routes prevail, battery swapping can complement the MCS network and support overall fleet electrification. For Europe, a coordinated approach to pilot deployment is therefore advisable, based on shared battery module profiles rather than isolated individual projects. Such an approach should also consider ongoing technical and organisational developments in MCS, incorporating and, where appropriate, leveraging the experience gained.

5.2 TCO

A key question concerns how battery swapping performs in terms of TCO and what differences arise from the various cost factors involved. Recent studies and pilot projects have partially examined these aspects for HDVs from the perspective of fleet operators, providing a range of insights. In the following, the most relevant cost factors and findings from these analyses are presented and, where possible, compared across battery swapping, depot charging, and public fast charging from the user's perspective. The most significant cost factors, in comparison with other battery-electric vehicle (BEV) charging options, include:

1. Energy costs
2. Opportunity costs arising from charging or swapping times and vehicle downtime
3. Vehicle battery size, cost, and payload losses
4. Battery lifetime and maintenance
5. Infrastructure and fixed costs
6. Energy arbitrage

Energy costs

The energy costs of battery-electric lorries are composed of several elements: the pure electricity price (procurement costs), grid charges (including demand charges), and pro rata depreciation costs for the charging infrastructure. In the case of depot charging, transport operators in Germany can - given well-planned and efficiently utilised infrastructure - charge at approximately €0.15 to €0.20 per kWh (Basma et al. 2021), particularly outside peak periods, provided sufficient grid capacity is available. Public high-power charging, by contrast, is more expensive. Depending on the provider and tariff, prices typically amount to around €0.30 to €0.50 per kWh or more (cf. Milence 2025)[2]. These charges include not only electricity procurement, but also grid fees, site-related costs, and a commercial margin.

In the context of (private) charging infrastructure in Germany, the so-called "2,500-hour rule" is also of relevance, as it shapes the tariff logic within the German system of annual demand-based grid charges for metered consumption points. For such consumption points, grid charges are composed of a demand charge, based on the maximum power drawn, and an energy charge, based on the total electricity consumed (Bundesnetzagentur 2025b). A key parameter in this system is the annual utilisation duration, defined as the quotient of the total energy drawn from the grid in a billing year (kWh) and the maximum annual power demand (kW) (Bundesministerium der Justiz 2005): Annual utilisation duration = kWh per year ÷ kW. The threshold of 2,500 hours per year represents a fixed inflection point within this framework: depending on whether the annual utilisation duration falls below or above this threshold, different pricing relationships between demand and energy charges apply. The specific tariff values vary by grid operator, voltage level, and applicable pricing schedule (Bundesnetzagentur 2015).

For charging infrastructure at a company's own site, this regulation is particularly relevant, as the simultaneous fast charging of multiple vehicles within short time windows can generate very high peak loads. These peaks drive up the annual maximum demand (kW), without a proportional increase in the total annual energy consumption (kWh). As a result, utilisation hours tend to decrease, potentially falling below the 2,500 hours per year threshold. By contrast, battery swapping can decouple power draw from vehicle operation. While overall energy demand remains high, battery charging can be smoothed over time and carried out at lower connection capacities across longer periods. This reduces peak demand at the grid connection point, increases utilisation hours, and can yield advantages in both grid dimensioning and the resulting tariff structure. A second important aspect concerns grid connection and expansion. Where reinforcement of the grid connection is required for charging infrastructure, a construction cost contribution may apply. The Bundesnetzagentur (2024) outlines a capacity-based model for this purpose, typically calculated using an arithmetic average over several years to reduce volatility. In practical terms, this means that, where site conditions and operational profiles permit, solutions that reduce the required connection capacity (such as load management, stationary storage, or indeed battery swapping with smoothed charging profiles) can positively influence not only ongoing grid charge components for fleet operators, but also reduce the overall cost burden associated with grid connection.

For battery swapping to be competitive, energy costs would need to be at most in a similar range to public charging or lower. In practice, pilot projects in China indicate that swap-capable lorries can already undercut diesel vehicles in terms of "fuel" costs:

Hub-to-Hub-long-haul logistics in multi-shift operation

This scenario addresses fixed, predictable routes with daily mileage of more than 400 to 500 kilometres and two to three shifts. Battery swapping replaces a conductive charging window of around 50 to 70 minutes – as is realistic given current HPC outputs of around 350–400 kW and an energy requirement of approximately 400 kWh under an idealised charging curve – with a swap process lasting six to ten minutes. With MCS power outputs above 1 MW expected to become available in the future, these charging windows could be reduced to roughly 30 to 40 minutes for comparable energy amounts. At the same time, however, the demands on grid connections, transformers and site expansion will increase. Battery swapping improves the predictability of operations and increases vehicle throughput. At the same time, the risks for users are reduced due to waiting times, potential incorrect use or blocking of charging points and unreliable reservations at public charging infrastructure resulting from external factors such as traffic congestion. The required connected load is generally in the single-digit megavolt-ampere (MVA) range, and the space required is less than for comparable HPC/MCS charging points. On busy routes with critical parking situations, this facilitates both line haul and encounter traffic services for all market players, as spaces are not blocked for other users, regardless of driving time regulations.

24/7 works transport with just-in-time requirements

This scenario focuses on works transport operations, with very high availability requirements and penalties for delays. The swapping process takes place in parallel with ramp and yard operations and does not cause any additional downtime. In addition, the situation in the user's yard is eased, as vehicles can be processed more quickly without parking spaces required for handling being blocked for long periods. This reduces the risk of process interruptions and significantly improves the utilisation of tractor units. More consistent load profiles facilitate the integration of photovoltaics or electricity price-stabilising procurement models and reduce performance-based grid charges.

Outlook: Autonomous 24/7 logistics

This scenario addresses heavily utilised transport fleets in continuous operation, where autonomous vehicles run almost continuously 24/7 – e.g. on defined routes or between hubs with fixed routing. Battery swapping replaces conductive charging processes and ensures a fully automated, driverless energy supply without operational downtime. Swap operations take between five and eight minutes and are triggered automatically by the vehicle itself or via fleet management software. This creates the technical conditions for operating autonomous vehicles at maximum capacity and avoiding unnecessary holding capacity at hubs. The integration of autonomous vehicles and battery swapping creates a fully decoupled, highly scalable transport operation – with a predictable energy supply, minimal downtime and maximum vehicle availability.

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[2] Figures for depot charging and public HPC based on expert discussions and desk research.

CATL reports savings of around 60,000 CNY (approximately €7,500) per 100,000 km compared with diesel-powered lorries (Randall 2025). Wang et al. (2023) estimate that battery swapping stations must charge at least 0.8 CNY/kWh (around €0.10/kWh) to operate profitably, although actual tariffs tend to be higher in order to cover station infrastructure and battery inventory costs. These costs are typically passed on to users through a combination of per-kWh pricing, swapping fees, and, where applicable, additional service or usage charges. Based on a short-haul use case in China, their analysis also shows that different charging modes are influenced not only by technical efficiency but also heavily by electricity prices and tariff structures. For fleet operators, this implies that unfavourable pricing structures (e.g. high service mark-ups) can offset the operational advantages gained from time savings. Conversely, operators can realise cost advantages under conditions of high utilisation and optimised energy procurement (e.g. by charging outside peak tariff periods) and pass these on to users in competitive markets (Börjesson et al. 2025). It should also be noted that conventional charging infrastructure, such as HPC sites, entails utilisation-dependent capital costs, which likewise contribute to the effective cost of conductive charging.

In their simulations for Europe, Börjesson et al. (2025) demonstrate that the relative economic performance of stationary charging versus battery swapping is influenced, amongst other factors, by assumptions regarding electricity prices and tariff structures. Crucially, the determining factor is often not the absolute energy price itself, but rather the interaction between energy costs, charging or swapping time, and the resulting time-related or opportunity costs.

Opportunity Costs Arising from Charging or Swapping Times and Downtime

The duration of energy replenishment has a significant impact on lorry productivity as well as on personnel and opportunity costs (Börjesson et al. 2025). Depot charging typically takes place over several hours at relatively low power (e.g. overnight) which, under ideal conditions, coincides with scheduled vehicle idle times or driver rest periods. In such cases, no additional downtime is incurred, if charging is fully integrated into operational breaks and the vehicle is not deployed in continuous multi-shift or overnight relay operations. At the same time, however, overnight charging reduces the specific utilisation of charging infrastructure, as no vehicle throughput is generated during these periods. This can negatively affect the economic amortisation of the infrastructure.

(Public) fast charging using HPC is significantly quicker than conductive charging at lower power levels but may still require charging stops of more than one hour for a battery-electric lorry, depending on the energy required and the available charging capacity[3]. The MCS has the potential to reduce these charging times further. However, such charging periods must either be integrated into legally mandated driving breaks or result in additional downtime where no operational idle time exists (for example in multi-shift operations). In practice, further delays may arise due to detours or waiting times (Börjesson et al. 2025), for instance if charging points are occupied or if charging power is shared under load management conditions during periods of high utilisation. Additional inefficiencies may occur when operational disruptions (e.g. traffic congestion) prevent adherence to scheduled charging windows, and charging points are already occupied by subsequent vehicles. For fleet operators, the use of (semi-)public charging infrastructure may entail additional operational effort in the form of driver logistics, to ensure vehicle movements to and from charging sites at the end and prior to the start of respective shifts.

Battery swapping represents the fastest option in this context: the complete exchange of a lorry battery can be carried out in approximately five to ten minutes, with industry already working towards even shorter swapping times (Ghosh 2025). This could potentially undercut the duration of a conventional diesel refuelling stop, resulting in virtually no additional downtime if stations maintain sufficient swapping capacity and battery inventory.

Shorter downtimes translate into lower idle costs, which primarily comprise driver-related expenses and the value of foregone transport activity. By way of illustration: in a "hub-to-hub long-haul, multi-shift" scenario, if a battery-electric lorry is required to charge for 50 to 70 minutes using HPC, additional costs of approximately €41.67 to €58.33 per charging event may arise for driver and vehicle. By contrast, with battery swapping (assuming a swapping duration of five to ten minutes or less) these opportunity costs are reduced to around €4.17 to €8.33.

Zhu et al. (2023) incorporate precisely this mechanism into a tonne-kilometre-based cost model and demonstrate that battery swapping becomes particularly economical in scenarios where high transport efficiency is required and charging time significantly constrains operations. Similarly, Deng et al. (2023) identify swapping times of only a few minutes as a key driver of productivity gains. Börjesson et al. (2025) operationalise this productivity dimension by translating time-related costs (i.a. such as driver time) into daily cost figures, thereby illustrating that even seemingly marginal differences in service time can lead to substantial cost impacts over multi-day operations. Wang et al. (2025) further confirm at the system level that battery swapping can enhance transport efficiency, in terms of both time and labour input, compared with fast charging.

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[3] Assumption: Charging power (CCS) 350 kW with an energy output of 400 kWh and a linear charging curve.

If driver shortages were to be mitigated in the future through autonomous driving, thereby eliminating driver-related labour costs, the relative cost advantage could diminish (Wang et al. 2025). However, Kelkar et al. (2024) emphasise that, in combination with autonomous vehicles, battery swapping can enable higher vehicle utilisation compared with MCS charging, and thus significantly increase overall transport efficiency.

Vehicle Battery Size and Cost

The required battery size varies depending on the charging approach and has a direct impact on acquisition and capital costs, as well as on the achievable payload of the vehicle. Transport companies, irrespective of the specific lorry type, optimise battery capacity with the objective of minimising daily operating costs (Börjesson & Proost 2025). Two principal reasons underpin this approach: first, battery capacity represents a substantial share of the total cost of a battery-electric lorry (Samet et al. 2023). Second, the weight of the battery reduces the permissible payload in weight-constrained operations in accordance with Directive 96/53/EC, thereby diminishing overall transport efficiency (Liimatainen et al. 2020).

Conductive charging often necessitates the use of comparatively large traction batteries to ensure sufficient driving range and reduce the frequency of charging stops during operation. According to a cost-benefit analysis by Wang et al. (2025), an optimal battery capacity of 600 kWh or more per lorry can be assumed to achieve ranges of approximately 400 to 500 km. Batteries of this capacity are correspondingly expensive and heavy.

Battery swapping, by contrast, enables a different optimisation approach: the onboard battery can be dimensioned smaller, as rapid swapping during operation compensates for reduced capacity. Calculations by Wang et al. (2025) indicate that, when utilising swapping networks, a medium-sized battery of around 450 kWh per lorry may be optimal to achieve comparable operational performance and cost efficiency per unit of transported freight as with conductive charging, without requiring excessively frequent stops.

The use of a smaller traction battery also reduces vehicle weight, thereby increasing the available payload. In addition, under a swapping model, the user often does not need to purchase the battery: the commercial vehicle can be offered at a lower upfront cost without the battery, which is instead provided by the swapping operator under a BaaS model. According to existing analyses, this decoupling can reduce the investment cost per battery-electric lorry by up to 50 % (Ghosh 2025). In practical terms, this means that a transport company only needs to finance the vehicle itself (excluding the battery), significantly lowering capital costs and depreciation. High upfront investments are thus converted into predictable operating expenses, potentially reducing the barrier to fleet electrification.

Battery Lifetime and Maintenance

A factor that is often overlooked is the impact of different charging approaches on battery health and maintenance costs. High charging power levels place greater stress on the traction battery and can reduce both calendar and cycle life. At the same time, efficiency losses - arising, for example, from heat generation - occur during the transfer of energy from the charging station to the vehicle. As a result, frequent charging at or near maximum power levels can accelerate component degradation or, due to the need for thermal management, reduce the usable overall capacity of the system (Shiledar et al. 2025; Dalir et al. 2025; Schneider et al. 2023). One potential consequence is that the traction battery may need to be replaced earlier over its lifetime due to degradation effects, thereby increasing overall costs.

Battery swapping offers two key advantages in this regard: first, stationary batteries can be charged at lower C-rates[4] over extended periods, as charging takes place outside the vehicle while the lorry continues operation with a fully charged battery. Second, in the event of a battery defect, the vehicle does not need to be taken out of service for an extended period, nor does it require prolonged workshop stays or substitution by a replacement vehicle. This aspect increases the operational availability of the fleet.

Infrastructure and Fixed Costs

For fleet operators, a key consideration is whether infrastructure investments are borne directly or procured via usage-based pricing. Accordingly, the costs associated with the development and operation of charging infrastructure are distributed differently depending on the model. Private depot charging requires the installation of charging stations at the operator's premises; for larger fleets, this can entail substantial investment, often accompanied by lengthy permitting processes. Public charging, by contrast, shifts the cost of infrastructure deployment to third parties such as charging point operators (CPOs). In this case, users pay a surcharge per kWh, which contributes to financing the infrastructure.

According to a study published by e-mobil BW GmbH in 2021, CAPEX for a 350 kW HPC point (i.e. hardware, planning, installation, commissioning, and grid connection, incl. transformer) amounts to more than €130,000 (Waxmann et

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[4] The C-rate (or C-coefficient) is a measure of a battery's charging and discharging speed in relation to its total capacity. A rate of 1C indicates that a battery is fully charged or discharged within one hour. A C-rate of less than 1 means that it takes longer than one hour; a C-rate of more than 1 means that it takes less than one hour.

al. 2021)[5]. In operational practice, however, these investment costs can be significantly higher depending on site-specific conditions. For example, if the nearest medium-voltage connection point is located at a considerable distance and extensive civil engineering works are required, expenditures for grid connection and construction can increase substantially. In addition, at logistics depots, unless designed from the outset, an optimal layout of charging points relative to the grid connection is rarely achievable, meaning that total costs for the charging point, including installation, can in some cases be roughly doubled[6]. Further cost factors arise from land use: charging bays typically do not replace existing parking or standing areas, as lorries must vacate the charging point once charging is complete. This necessitates additional parking capacity, thereby increasing space requirements and associated costs. According to Plötz et al. (2025), CAPEX for an MCS station with four charging points (including hardware, installation and grid connection) is expected to range between approximately €1.33 million and €1.47 million in 2025. For Germany alone, Speth et al. (2022) note that, along heavily trafficked corridors, charging sites may need to be equipped with up to 13 charging points even in early market phases to accommodate the anticipated ramp-up of battery-electric lorries. Consequently, in addition to high infrastructure costs, substantial land requirements and associated expenses arise, particularly along major motorway networks.

Battery swapping stations potentially entail the highest infrastructure costs. Such stations must be equipped with fully automated swapping systems and maintain a buffer stock of replacement batteries. According to Bernard et al. (2022), investment costs, depending on battery capacity and the number of charging bays, range between USD 1 and 1.5 million per station for heavy-duty applications. Approximately half of these costs are attributable to the battery inventory itself (Cui et al. 2023). Whereas the achievable energy throughput, like conventional charging stations, is fundamentally limited by the available grid connection capacity, battery swapping stations can achieve higher effective vehicle throughput under sufficient utilisation. This is due to the decoupling of vehicle dwell time from battery charging, making operations less dependent on perfectly synchronised charging and dispatch schedules. A study by Zhu et al. (2023), for example, indicates that battery swapping becomes most economically viable once a station reaches a utilisation rate of around 43 %. At this level, the high fixed investment costs can be distributed across a larger number of vehicles, potentially enabling lower per-kWh prices for users. For transport operators as well as station operators, this implies that battery swapping can be economically advantageous in corridor, shuttle, or hub-to-hub operations where sufficient throughput is achieved to spread fixed costs. At the same time, the required land footprint at these critical nodes can be reduced compared with stationary charging solutions.

Energy Arbitrage

Energy arbitrage can enhance the revenue streams of battery swapping station operators, but it should not be considered a primary value driver. In this context, swapping stations may be designed with bidirectional capabilities to provide grid services (Jerratsch et al. 2025; He 2025). Arbitrage potential arises from time-variable electricity procurement prices and local generation sources, such as photovoltaic systems or power purchase agreements. These opportunities can be utilised opportunistically, provided that they do not compromise the core operational objectives of battery swapping from the user's perspective. The fundamental business model should therefore remain centred on the reliable provision of swapping capacity, characterised by high availability and clearly defined swapping times.

Comparative Calculation on Stationary Charging and Batter Swapping

To translate the previously discussed cost drivers (energy procurement, opportunity costs, battery and vehicle capital costs, infrastructure CAPEX, and payload effects) into a more tangible framework, an illustrative comparative calculation is presented below for fleet operators in Germany. For this, two operational profiles are considered:

- 80,000 km per year in regional operations, with predominantly planned depot charging
- 150,000 km per year in long-haul operations, with a higher share of non-depot-based energy supply

The results are presented as cost ranges to transparently reflect uncertainties in key parameters (including electricity prices, swapping fees, and infrastructure and battery CAPEX). These illustrative calculations are intended to provide an indication of orders of magnitude and key cost drivers; they do not constitute a forecast for a specific site or fleet. The ranges arise from parameters that are currently uncertain or highly location-dependent and are therefore deliberately expressed as bandwidths. In particular, the following limitations apply to the calculations:

- Site- and grid-specific effects (e.g. actual available connection capacity, construction cost contributions, specific grid tariff structures and peak load impacts) can vary significantly between depots; these are represented only through simplified assumptions.
- Pricing structures for public charging and battery swapping (per-kWh prices, swapping fees, and potential additional service charges) are currently market-and contract-specific; actual conditions may differ considerably.
- Infrastructure utilisation and operational organisation (e.g. how many lorries share a depot charging point, temporal load smoothing, charging windows) have a major influence on annualised infrastructure costs; simplified utilisation assumptions are applied in the model.
- Excluded factors include, i.a., detour and queuing effects (waiting times and route deviations), potential fleet resilience benefits (e.g. increased availability through battery pooling), as well as any impacts arising from specific subsidy schemes or individual financing and residual value assumptions.

The annual cost blocks per lorry are calculated as follows:

(1) Depot and Public Charging

$C_{Depot,Total} = (C_{E,Mix} + C_{Opp,HPC} + C_{Veh} + C_{Bat} + C_{Infra,CAPEX} + C_{Infra,Operation}) * M(B_{Depot})$

with energy procurement:

$C_{E,Mix} = E * [(1\text{-}p) * \text{ƒ}_{Depot} + p * \text{ƒ}_{HPC,public}]$ with $E = KM * k$

Opportuniy costs: $C_{Opp,HPC} = (p * E * \text{ƒ}_{Opp}) / P_{Peak}$

Vehicle CAPEX (exluding battery): $C_{Veh} = \text{ƒ}_{Veh} * 365$

Battery CAPEX : $C_{Bat} = \text{ƒ}_{Bat} * B_{Depot} * 365$

Depot charging infrastructure CAPEX: $C_{Infra,CAPEX} = \text{ƒ}_{Infra} / (n_{Lorry} * L)$

Depot charging infrastructure (Operation):

$C_{Infra,Operation} = (\text{ƒ}_{Infra} * c_{Operation}) / n_{Lorry}$

Payload loss multiplier: $M(B_{Depot}) = V / (V\text{-}w * B_{Depot})$

(2) Swapping (BaaS)

$C_{Swap,Total} = (C_{E,Swap} + C_{Service,Swap} + C_{Opp,Swap} + C_{Veh}) * M(B_{Swap})$

with energy procurement:

$C_{E,Mix} = E * [(1\text{-}p) * \text{ƒ}_{Depot} + p * \text{ƒ}_{HPC,Public}]$ with

$E = KM * k$: $C_{E,Swap} = E * \text{ƒ}_{Swap}$ mit $E = KM * k$

Swap Service Fee: $C_{Service,Swap} = E * s_{Swap}$

Opportunity costs: $C_{Opp,Swap} = N_{Swap} * c_{Swap}$ with $N_{Swap} =$

$E / (u * B_{Swap})$,$u \in [0.8, 0.9]$ and $c_{Swap} = t_{Swap} * \text{ƒ}_{Opp}$

Vehicle CAPEX (exluding battery) : $C_{Veh} = \text{ƒ}_{Veh} * 365$

Payload loss multiplier: $M(B_{Swap}) = V / (V\text{-}w * B_{Swap})$

Where charging processes can largely take place during scheduled idle periods at the depot, the results for regional operations with predominantly planned depot charging (80,000 km per year) indicate that virtually no additional opportunity costs arise. In this case, the focus shifts to energy procurement costs (€/kWh) and CAPEX-driven cost components, particularly those associated with the battery and depot charging infrastructure. Battery swapping can only compete economically if the swap service fee and the associated energy pricing are sufficiently low to meaningfully offset the capital and operating costs of both the battery and the depot charging infrastructure.

In long-haul operations with a higher share of non-depot-based energy supply (150,000 km per year), the weighting shifts: limited depot charging windows and a greater reliance on (semi-)public HPC energy increase both ongoing OPEX for energy and opportunity costs associated with charging times. It is precisely in this context that the illustrative calculation highlights the potential role of battery swapping: higher usage-based fees (swap service fees) can be partially or fully offset by reduced vehicle downtime. In addition, a smaller battery configuration and the resulting lower payload losses can positively influence total costs. At the same time, a BaaS model can significantly reduce battery and depot charging infrastructure CAPEX for fleet operators.

Key Takeaways

Battery swapping can improve the TCO for fleet operators under conditions of high utilisation, tight time constraints,

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[5] OPEX such as maintenance, repairs and internet connection are excluded here.

[6] Figures based on expert discussions.

Parameter	Variable	Range	Source/Note
Annual mileage	KM	80,000 km/year	see TNO et al. (2018)
Energy consumption (motorway & urban)	k	1.5 kWh/km	see Shoman et al. (2023)
Proportion of public charging	p	0–5 %	see Suzan & Mathieu (2021)
Opportunity costs (staff, vehicle and transport service)	f_{Opp}	50 €/h	based on expert discussions
Depot charging infrastructure (175 kW) CAPEX	f_{infra}	45,000–67,500 €	see Bernard et al. (2022); Waxmann et al. (2021)
Vehicle CAPEX (excluding battery)	f_{Veh}	59 €/day	see Börjesson et al. (2025)
Battery CAPEX	f_{Bat}	0.083 €/kWh/day	vgl. Börjesson et al. (2025)
Electricity prices (Depot)	f_{Depot}	0.15–0.20 €/kWh	see Hacker et al. (2025)
Electricity prices (Public)	$f_{HPC,public}$	0.40–0.60 €/kWh	see Milence (2026) and based on discussions with experts
Electricity prices (Swap)	f_{Swap}	0.25–0.50 €/kWh	Assumption of arbitrage, whereby swapping station operators can offer users low kWh prices
Swapping fee (Swap)	s_{Swap}	0.03-0.10 €/kWh	see Börjesson et al. (2025)
Battery size (Depot)	B_{Depot}	550–650 kWh	see Link & Plötz (2022)
Battery size (Swap)	B_{Swap}	450-550 kWh	see Wang et al. (2025)
Charging power (Public)	P_{peak}	350 kW	see Basma & Schmidt (2025)
Time (Swap)	t_{Swap}	5–10 min	see Li et al. (2024)
Depot charging infrastructure (operation & maintenance)	$c_{Operation}$	1.20%	see Bernard et al. (2022)
Lorries/charging point	n_{Lorry}	1–4 Lorries/ charging point	see Göckeler et al. (2023)
Depreciation period (linear)	L	9 years	see Bundesministerium der Finanzen (2000)
Payload	V	27 t	see Basma et al. (2021)
Battery weight factor	w	0.005 t/kWh	see Khan et al. (2023); Basma et al. (2021)

Table 1: Definition of parameters for 80,000 km/year in regional transport with predominantly scheduled depot loading

Cost breakdown (€/year per lorry)	Depot & public charging	Swapping (BaaS)
Energy procurement	18.000-26.400 €	30.000-60.000 €
Opportunity costs	0-860 €	1.240-2.280 €
Swap service fee	–	3.600-12.000 €
Payload loss costs	6.530-10.510 €	5.125-10.870 €
Vehicle CAPEX (excluding battery)	21.540 €	21.540 €
Battery CAPEX	16.660-19.690 €	–
Depot charging infrastructure CAPEX	1.250-7.500 €	–
Depot charging infrastructure (Operation)	140-810 €	–
TOTAL	**64.120-87.310 €**	**61.500-106.690 €**

Table 2: Cost categories for 80,000 km/year of regional transport with predominantly scheduled depot charging

and larger fleet sizes, particularly through reduced vehicle downtime and lower charging infrastructure CAPEX. In addition, grid expansion, especially at the medium-voltage level, often takes several years and is typically governed by a “first come, first served” principle. In this context, battery swapping can help alleviate constraints for individual operators. Looking ahead, the advent of autonomous driving may alter the current logic of driving time regulations and charging windows. In such a scenario, battery swapping could enable more continuous, 24/7 vehicle operation.

The available body of research indicates that battery swapping cannot be assessed economically as a “one-size-fits-all” solution. Rather, outcomes depend heavily on the specific use case (route lengths, time windows and daily mileage), as well as on system parameters (battery size, charging and swapping times, and infrastructure availability), and the underlying business model (battery ownership versus BaaS, pricing structures and fee models). It is important to note that empirical data on real-world operating costs for heavy-duty swapping fleets remains limited. Across the studies reviewed in this white paper, there is consistent acknowledgement of significant uncertainties in key assumptions and parameterisation.

Despite differing assumptions, the literature provides indicative cost ranges and orders of magnitude. Börjesson et al. (2025), in their European multi-day trip model, estimate daily costs per truck that, depending on the scenario and parameter assumptions, range from approximately €961 to €1,248 for battery swapping, while stationary charging in their model reaches around €1,060 to €1,494 per day. These figures suggest, as a general point of reference, that battery swapping can, under certain assumptions, offer lower daily costs per vehicle for fleet operators.

In the Chinese context, Zhu et al. (2023), based on a tonne-kilometre-oriented cost model, show that battery swapping can be economically viable particularly in the medium recharge-distance range and, given sufficiently high station utilisation, can offer advantages over stationary charging. Wu et al. (2021) similarly confirm in an application-oriented cost study that battery swapping can be economically attractive in the scenarios examined. However, the results depend strongly on how infrastructure costs are allocated to fleet operators (e.g. pure usage-based models versus leasing or rental arrangements for stations) and on the density of the swapping network.

Börjesson et al. (2025), in the context of TCO, modelled the costs per trip and per day for multi-day long-haul operations in Europe. They conclude that, under current conditions, swap-capable lorries can provide a cost advantage for fleet operators of up to 17 % compared with vehicles relying on stationary charging. This advantage is projected to persist until 2035, albeit at a reduced level of up to around 10 %. The primary drivers of this advantage are identified as battery-related capital costs, energy procurement costs in (semi-) public charging contexts, and opportunity costs arising from

Parameter	Variable	Range	Source/Note
Annual mileage	KM	150,000 km/year	see Zähringer et al. (2024); Unterlohner (2021)
Energy consumption (motorway & urban)	k	1.8 kWh/km	see Shoman et al. (2023)
Proportion of public charging	p	25–40 %	see Suzan & Mathieu (2021)
Opportunity costs (staff, vehicle and transport service)	f_{Opp}	50 €/h	based on expert discussions
Depot charging infrastructure (175 kW) CAPEX	f_{infra}	150,000–250,000 €	see Bernard et al. (2022); Waxmann et al. (2021)
Vehicle CAPEX (excluding battery)	f_{Veh}	59 €/day	see Börjesson et al. (2025)
Battery CAPEX	f_{Bat}	0.083 €/kWh/day	see Börjesson et al. (2025)
Electricity prices (Depot)	f_{Depot}	0.15–0.20 €/kWh	see Hacker et al. (2025)
Electricity prices (Public)	$f_{HPC,public}$	0.40–0.60 €/kWh	see Milence (2026) and based on discussions with experts
Electricity prices (Swap)	f_{Swap}	0.25–0.50 €/kWh	Assumption of arbitrage, whereby swapping station operators can offer users low kWh prices
Swapping fee (Swap)	s_{Swap}	0.03-0.10 €/kWh	see Börjesson et al. (2025)
Battery size (Depot)	B_{Depot}	600–700 kWh	seeLink & Plötz (2022)
Battery size (Swap)	B_{Swap}	450-550 kWh	see Wang et al. (2025)
Charging power (Public)	P_{peak}	350 kW	see Basma & Schmidt (2025)
Time (Swap)	t_{Swap}	5–10 min	see Li et al. (2024)
Depot charging infrastructure (operation & maintenance)	$c_{Operation}$	1.20%	see Bernard et al. (2022)
Lorries/charging point	n_{Lorry}	1–8 Lorries/ charging point	see Göckeler et al. (2023)
Depreciation period (linear)	L	9 years	see Bundesministerium der Finanzen (2000)
Payload	V	27 t	see Basma et al. (2021)
Battery weight factor	w	0.005 t/kWh	see Khan et al. (2023); Basma et al. (2021)

Table 3: Definition of parameters for 150,000 km/year of long-distance transport with an increased proportion of non-depot-based energy supply

Cost breakdown (€/year per lorry)	Depot & public charging	Swapping (BaaS)
Energy procurement	57.380–97.200 €	67.500–135.000 €
Opportunity costs	9.640–15.430 €	2.780-5.120 €
Swap service fee	–	8.100–27.000 €
Payload loss costs	13.630–32.900 €	9.080-21.390 €
Vehicle CAPEX (excluding battery)	21.540 €	21.540 €
Battery CAPEX	18.180–24.240 €	–
Depot charging infrastructure CAPEX	2.080–27.780 €	–
Depot charging infrastructure (Operation)	230–3.000 €	–
TOTAL	**122.680–222.090 €**	**109.000-210.050 €**

Table 4: Cost categories for 150,000 km/year of long-distance transport with a higher proportion of non-depot-based energy supply

charging processes. Against this background, the authors argue that battery swapping should not be overlooked by the EU when designing measures to support the electrification of HDVs in pursuit of climate targets.

Across the body of literature, recurring conditions can be identified under which battery swapping may be more economical than stationary charging from a fleet operator's perspective. First, the advantage of battery swapping increases with rising time-related costs, particularly in operations with tight time windows, high tour frequency, or scenarios in which additional charging stops would necessitate additional vehicle deployment or multi-shift operations. Wang et al. (2025) and Börjesson et al. (2025) demonstrate that time and labour costs are often the dominant lever in many use cases. Second, economic viability improves with higher utilisation of swapping infrastructure. Zhu et al. (2023) quantify this explicitly, identifying battery swapping as the most cost-efficient concept for heavy-duty battery-electric vehicles when station utilisation exceeds approximately 43 %. While such thresholds are context-specific, they illustrate a general principle also highlighted qualitatively by Speth and Funke (2019): battery swapping is capital-intensive and requires sufficiently high utilisation rates to become competitive. Third, pricing structures play a critical role. Even where time savings are significant, excessively high swapping fees can offset the economic advantage. Börjesson et al. (2025) indicate a model-based threshold of around €50 per swap as a reference point. Conversely, this implies that battery swapping becomes particularly attractive when pricing remains below the level at which productivity gains are negated. Fourth, the relative advantage is closely linked to battery size, and thus to payload and CAPEX effects. Where stationary charging necessitates large batteries, capital tied up in the battery and payload losses increase. In such cases, battery swapping can offer economic benefits via smaller or medium-sized batteries (Wang et al. 2025; Zhu et al. 2023).

The body of research thus indicates that battery swapping in the HDV segment can, on the one hand, offer cost advantages for users compared with vehicles relying solely on stationary charging. At the same time, it presents viable opportunities for business models for operators of swapping stations. On the other hand, a broader deployment of battery-electric lorries facilitated by battery swapping could contribute to advancing decarbonisation strategies within the European Union.

6. Recommendations for Action

Based on the findings of the preceding chapters, a set of recommendations for action is formulated. These are intended to serve as a stimulus for deeper cross-sector collaboration among key stakeholders from policy, industry and research, with the aim of advancing cooperation in the further development of battery swapping for HDVs in Europe in a targeted manner. These recommendations should be understood as individual building blocks, which are in part complementary and should be progressively developed and implemented by the relevant stakeholders.

Use Case Focus

Battery swapping demonstrates its greatest value in operational contexts characterised by high daily mileage, tight scheduling cycles, and constrained grid and land resources. In line-haul and hub-to-hub operations with multi-shift deployment, battery swapping enables the decoupling of energy replenishment from route planning, reduces downtime, and increases potential vehicle throughput. A targeted market introduction along a limited number of clearly defined transport corridors, anchored by key depots (e.g. freight logistics centres), is strategically advisable. Such an approach can accelerate demand aggregation, learning curve effects, and the resolution of regulatory issues.

Standardisation and Technical Reference Architecture

A central prerequisite for the successful deployment of battery swapping is the establishment of cross-manufacturer standards. This includes harmonisation of battery module geometry, locking mechanisms, HV and cooling interfaces, as well as communication protocols. Without such interoperability, there is a risk of fragmented, proprietary solutions that limit scalability and increase operational complexity. Building on this, a common technical reference architecture should be developed to define system boundaries, interface specifications and operational requirements for swapping systems. This would provide planning certainty for manufacturers, infrastructure operators and fleet operators alike, while facilitating integration into existing energy and digital ecosystems. Standardisation efforts should be coordinated at the European level and aligned with ongoing activities in international bodies. Close collaboration between industry, research institutions and standardisation organisations (such as those led by DIN) is essential to ensure both technical feasibility and broad market acceptance.

Business Model and Financing

The target model separates ownership of vehicles, infrastructure and batteries, and is based on a BaaS approach. One option is the establishment of a dedicated battery asset company to professionally manage residual value and obsolescence risks. Pricing structures may combine energy tariffs, swap fees, and contractually defined availability-based SLAs. Battery pool sizing should be service-level-driven, e.g. based on defined targets for waiting times and arrival variability along specific corridors, rather than relying on fixed "batteries-per-vehicle" ratios.

A parallel fallback via high-performance HPC/MCS charging points at the site can reduce single-point-of-failure risks and ensure service continuity. For OEMs, such a model shifts the distribution of investments and revenues between vehicle sales, battery-related business, and service offerings. Accordingly, roles, incentive structures and data interfaces across OEMs, operators and asset companies must be explicitly defined (e.g. through participation models, long-term maintenance and performance service agreements, and battery swapping service option packages) so that vehicle sales and after-sales business are not decoupled but continue to complement one another.

Grid and Energy System Integration

Early planning of medium-voltage grid connections, based on realistic capacity corridors, is essential. Stationary or unused storage capacities should primarily be utilised for load smoothing and the reduction of demand charges; participation in grid services markets may be considered as a supplementary option but should not be treated as a primary revenue source. The integration of on-site photovoltaic generation and electricity supply contracts that stabilise energy prices can improve the overall cost base, provided that the load profiles of swapping operations are aligned with procurement strategies. From an operational and reliability perspective, a redundancy concept should be implemented, including at least two swapping lanes per station, as well as clearly defined emergency and maintenance procedures to ensure high availability and safety.

Operations, Safety, and Digital Platform

For scalable operations, a platform architecture should be established that integrates reservation systems, access management, billing, and battery condition data, while ensuring interoperability with fleet and energy management systems through open interfaces. Service-level targets for swapping time, system availability and error rates must be clearly defined and contractually binding. These should be supported by predictive maintenance, standardised spare parts management, and regular audits. Comprehensive data collection and analysis across the entire swapping process is essential to continuously validate both technical maturity and underlying economic assumptions.

Digital Interoperability and Cybersecurity

To enable seamless integration of battery swapping into dispatch and fleet operations, an open protocol is required for booking, identification, billing, as well as availability and condition data, while simultaneously preventing the emergence of platform monopolies. Across the entire value chain - vehicle, battery, station and backend - security requirements should be standardised (e.g. in line with IEC 62443), regularly audited, and supported by secure update and key management systems. This is essential to prevent operational disruptions and manipulation of what may evolve into a critical energy infrastructure.

Cross-Border Operations and Battery Return Logistics

For cross-border operations, a harmonised process chain across the EU is required. Key elements include standardised battery identification, interoperable documentation of SoH and SoC, and a clearing mechanism that enables settlement of battery swaps across different operators. Customs and transport regulations must be clarified regarding temporary transfers of ownership and the return logistics of batteries. Under an open standard, a clearing-house approach may be practical, allowing kWh flows, usage fees, and any deposit schemes to be balanced between operators. Vehicles should always retain the capability for conductive charging to avoid bottlenecks in battery return logistics. Billing models should account for the state of charge of returned batteries, as well as any quality deviations, which can be assessed based on the documented SoH.

Access Policy in Open Corridors

A scalable model requires a clearly defined access policy that regulates contractual relationships between anchor fleets, subcontractors, and operators. This necessitates robust identity and access management at both vehicle and company level, ensuring that slot bookings, billing, and liability are clearly assigned. Volume-based pricing structures for anchor fleets are advisable, alongside standardised terms for subcontractors with defined service-level priorities.

Regulation, Billing, and Compliance

For compliant operation, a clearly defined conformity pathway, aligned with the relevant authorities, is required. Key priorities include metrologically compliant kWh-based billing, including the treatment of the returned state of charge, as well as unambiguous rules governing ownership, liability and insurance of battery assets. In addition, consistent requirements must be established for construction, fire protection, and operational safety of swapping stations. Furthermore, variable battery weights and their implications for vehicle approval and payload must be addressed through binding regulations. Early and institutionalised dialogue with standardisation bodies and market surveillance authorities helps to reduce project risks and shorten approval timelines.

Research, Development, and Skills

Priority areas in research and development include robust battery pack and locking systems capable of sustaining high cycle numbers, rapid SoH diagnostics, the management of ageing variability, advanced thermal management, and interfaces to the circular economy (including refurbishment, second-life applications and high-quality recycling). Open reference stations, operated jointly by industry and research institutions as "living laboratories", can enable the validation of components, software, processes and business models under real-world conditions. The publication of independent evaluations helps to build trust and accelerate learning curves. In addition, targeted training programmes for workshops, operators, users, and emergency services such as fire brigades, can enhance both safety and acceptance in operational practice.

Energy Arbitrage

Energy arbitrage can provide an additional revenue stream for operators of battery swapping stations, but it should not be treated as the primary value driver. To enable this, swapping stations may be designed with bidirectional capabilities to offer grid services (Jerratsch, Killian & Marker 2025; He 2025). Arbitrage opportunities arise from time-variable electricity procurement prices and local generation sources, such as photovoltaic systems or power purchase agreements. These opportunities should be leveraged opportunistically, without compromising the core operational objectives of battery swapping from the user's perspective. The fundamental business model should remain focused on the reliable provision of swapping capacity, characterised by high availability and clearly defined swapping times.

Battery swapping can improve TCO under conditions of high utilisation and larger fleet sizes, particularly through reduced vehicle downtime and lower grid connection requirements. In addition, grid expansion, especially at the medium-voltage level, can take several years and is typically governed by a "first come, first served" principle. In this context, battery swapping can help alleviate constraints for individual operators. Looking ahead, the gradual introduction of autonomous driving may alter the current framework of driving time regulations and charging windows. In such a scenario, battery swapping could enable more continuous, 24/7 vehicle operation.

7. Conclusion

»Swapping is recognized as an effective tool.«

In summary, battery swapping can be classified as a complementary technology to depot charging, HPC and, prospectively, MCS charging for the ramp-up of battery-electric heavy-duty transport in Europe. Its specific contribution lies in the decoupling of energy replenishment from vehicle operations: swapping processes carried out within minutes reduce planned downtime, enable grid- and cost-optimised charging of batteries at the station, and thereby create additional operational flexibility in high-frequency, tightly scheduled applications. At the same time, for large-scale deployment, the strategic focus of European policy and industry remains on conductive charging solutions. International experience, particularly from China, demonstrates the technical and organisational feasibility of battery swapping at industrial scale, but cannot be directly transferred to Europe due to differing framework conditions.

Feedback from practical applications presents a consistent picture: battery swapping is recognised by many as an effective lever in clearly defined use cases, while the primary ramp-up is still expected to be driven by HPC and, in future, MCS. At the same time, insights from expert interviews and operational experience indicate that an exclusive focus on HPC/MCS already encounters (or may encounter) scaling limitations due to grid connection capacities, land availability, site density, and the availability of charging points (see Sections 4.4 and 5.1). Across stakeholder groups, clear entry conditions are identified: cross-manufacturer mechanical interoperability of battery modules, defined HV, cooling and communication interfaces, as well as a compliant billing pathway, including the treatment of the returned SoC. In addition, ownership, liability, and insurance models for BaaS must be clarified. From an operational perspective, redundancy and fallback options via conductive charging points are required to manage single-point-of-failure risks associated with swapping stations. A digital platform integrating reservation systems, access management, billing, and battery condition data is regarded as essential infrastructure for ensuring transparent control of availability and throughput.

From an economic perspective, battery swapping is initially more capital-intensive on the infrastructure side than a single HPC or MCS charging point, as it requires not only automation but also the provision and management of a battery pool (see Section 5.2). However, when compared with an MCS site comprising multiple charging points and, where applicable, buffer storage, the overall investment requirements are of a similar order of magnitude. The economic advantage does not arise inherently, but rather from operational fit and utilisation: the more homogeneous the fleet, the more predictable the operating cycles, and the higher the throughput, the more likely it is that opportunity cost advantages can be realised through battery swapping. In this context, battery pool sizing should not be understood as a fixed "batteries-per-vehicle" ratio, but rather as a service-level-based parameter (e.g. defined by waiting times and arrival variability). At the system level, battery swapping can also contribute to smoothing load peaks, as batteries can be pre- and post-charged at moderate power levels. While this does not eliminate the need for overall grid expansion, it can make local grid integration more manageable and provide greater short-term flexibility.

For a robust European roll-out, three key workstreams can be identified. First, the technical reference architecture: a cross-manufacturer standard for battery swapping and interfaces (for mechanics, HV systems, cooling, and communication) combined with transparency regarding SoH and SoC, as well as conformity and interoperability testing. This is essential to prevent fragmented, proprietary solutions and to create investment certainty. Initial developments in this direction can already be observed both in Asia and in Europe (see Chapter 3). Second, the compliance pathway: this includes metrologically compliant kWh-based billing that accounts for the returned battery state, clearly defined ownership and liability frameworks, and consistent requirements for construction, fire safety, and operational safety. Third, operational and market organisation: this encompasses open protocols and interfaces, clearly defined access concepts for anchor fleets and subcontractors, redundancy within stations, and - for cross-border operations - a harmonised clearing and return logic. Such a framework enables batteries to be settled and redistributed across operator boundaries.

Timing is critical. Europe already possesses key normative foundations in the areas of communication and safety, as well as a rapidly evolving MCS ecosystem. However, several open issues - most notably mechanical interoperability, the integration of billing and market supervision frameworks, and the demonstration of robust operational SLAs under real-world conditions - are time-sensitive. If their resolution is delayed, the likelihood increases that external (non-European) solutions will establish de facto standards, which Europe would then follow rather than help to shape. At the same time, there is no "perfect" moment to act. A pragmatic approach is to position battery swapping explicitly as a complement to the MCS ramp-up and to initiate coordinated, open-standard corridor pilots with anchor fleets in the near term. This would allow technical, regulatory and economic questions to be addressed under real operational conditions, accelerate learning curves, and avoid technological lock-in, while simultaneously advancing the electrification of heavy-duty transport through a complementary mix of technologies.

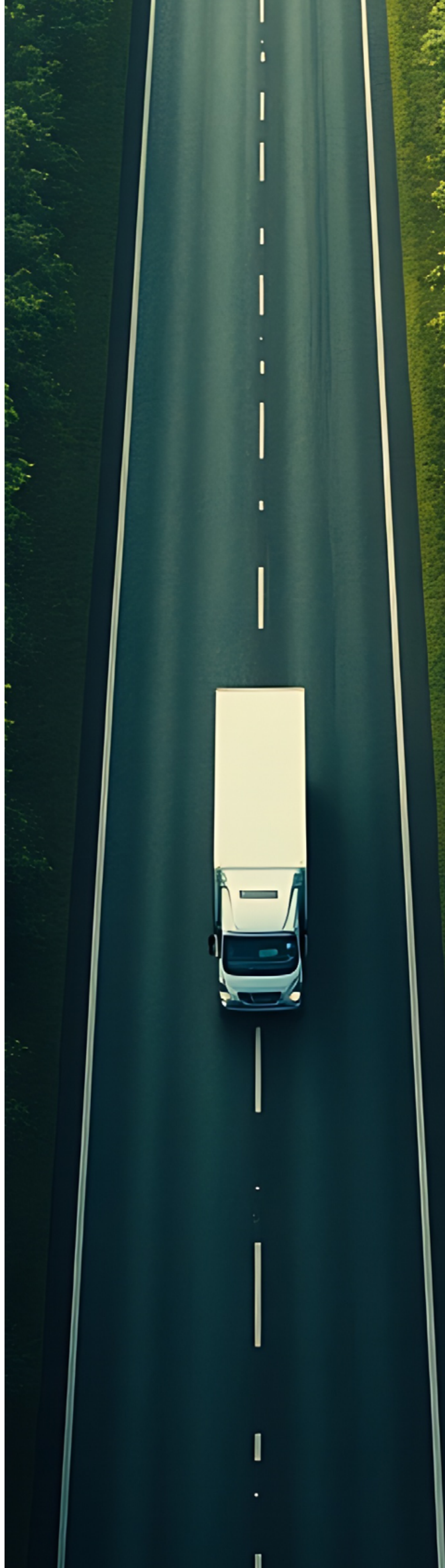
Image: The Little Hut – stock.adobe.com

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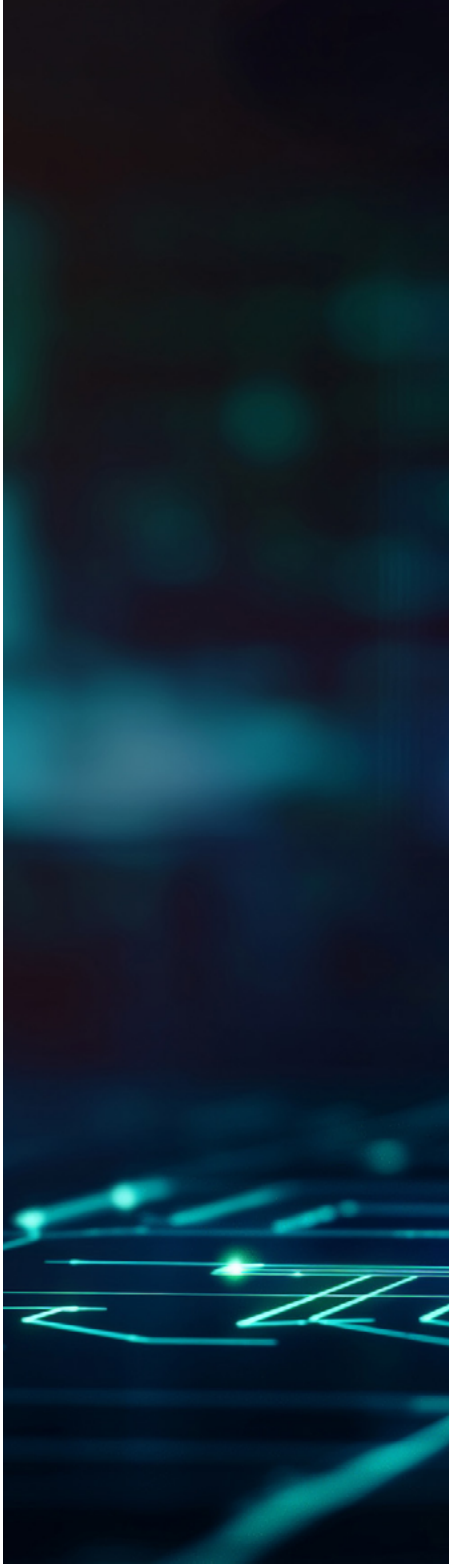
List of Abbreviations

AFIR	Alternative Fuels Infrastructure Regulation
BaaS	Battery-as-a-Service
BMV	Federal Ministry of Transport
CAPEX	Capital Expenditures
CATL	Contemporary Amperex Technology Co. Limited
CCS	Combined Charging System
CPO	Charging Point Operator
GAC	Guangzhou Automobile Group
HPC	High Power Charging
HV	High Voltage
IEC	International Electrotechnical Commission
JAC	Anhui Jianghuai Automobile
MCS	Megawatt Charging System
MVA	Megavolt-ampere
NEV	New Energy Vehicle
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditures
SBS	Swappable Battery System
SLA	Service Level Agreement
SME	Small and Medium-sized Enterprise
SoC	State of Charge
SoH	State of Health
SVR	Sachverständigenrat zur Begutachtung der gesamtwirtschaftlichen Entwicklung
TCO	Total Cost of Ownership
TWh	Terawatt-hour



Contact

Fraunhofer-Institut for Material Flow
and Logistics IML

Philipp Müller, Daniela Kirsch
Joseph-von-Fraunhofer-Straße 2-4
44227 Dortmund

Tel. +49 231 9743-0
verkehrslogistik@iml.fraunhofer.de
www.iml.fraunhofer.de/verkehrslogistik