PUBLISHER

TÜVRheinland®
Precisely Right.

INSTITUTE FOR INNOVATION AND TECHNOLOGY

GRID INTEGRATION OF HEAVY COMMERCIAL VEHICLES

An Impulse Paper by
the Accompanying Research Elektro-Mobil

IMPRINT

Publisher

TÜV Rheinland Consulting GmbH
Institute for Innovation and Technology (iit) in the VDI/VDE Innovation + Technik GmbH
On behalf of the Federal Ministry of Economic Affairs and Climate Action (BMWK)
Dr. Sören Grawenhoff, Am Grauen Stein, 51105 Cologne, soeren.grawenhoff@de.tuv.com

Authors

Ilona Friesen (TÜV Rheinland Consulting GmbH)
Matthias Trunk (TÜV Rheinland Consulting GmbH)
Timon Kiriazis (TÜV Rheinland Consulting GmbH)
Sarah Vogl (TÜV Rheinland Consulting GmbH)

Design

LHLK Agentur für Kommunikation GmbH
Hauptstraße 28
10827 Berlin

Contact Information

begleitforschung-elektro-mobil@de.tuv.com
LinkedIn
"Elektro-Mobil" funding programme

Disclaimer

The implementation of this impulse paper was supported by a number of organisations involved in the "Elektro-Mobil" funding programme. The accompanying research Elektro-Mobil is responsible for the content of this impulse paper and for the editorial work. All the projects involved in this impulse paper are listed below.

Contributing Projects

AMELIE 2	ELINA	evTrailer2	KoLa	SPIRIT-E
E|MPOWER	ELMAR	HV-MELA-BAT	MEGA-LADEN	UniSwapHD
eHaul	enERSyn	IDEAL	NEFTON	

Cover Picture

Shutterstock

Date

July 2024

EXECUTIVE SUMMARY

Heavy goods transport is responsible for around a quarter of transport-related CO_2 emissions, which is why zero-emission heavy goods transport is necessary to achieve the climate targets. In order to meet the political targets, manufacturers of heavy goods vehicles are converting some of their models to battery-electric drive trains. Battery-electric trucks with gross vehicle weights up to 26 t and ranges up to 300 km are already market-ready and in serial production at several manufacturers. With these vehicles, use cases such as the "last mile" are already feasible today and the available charging capacities are sufficient to fully charge the vehicles overnight.

The first models with a gross vehicle weight of up to 44 t and with ranges that are also suitable for long-haul transport are now in (pre-)serial production as well. However, these vehicles require higher charging capacities in order to be able to recharge sufficiently during the legally mandated break times. However, the necessary fast-charging infrastructure with charging capacities of over 500 kW is still in the demonstration phase. The finalisation of the Megawatt Charging System (MCS) with charging capacities of over 1000 kW is expected in 2024.

In addition to megawatt charging, other technologies for the electrification of long-haul transport are conceivable. The projects of the "Elektro-Mobil" funding programme are working on the development of these technologies, which also include a battery swapping system and electric road systems such as overhead lines and induction coils. The required grid connection power can be limited by controlling individual charging processes. Furthermore, bidirectional charging of heavy-duty vehicles with their enormous battery capacities can open up additional business models such as providing system services.

In this impulse paper, the accompanying research of the "Elektro-Mobil" funding programme formulates a status report on the grid integration of electrified heavy-duty vehicles. The basics of grid integration, various vehicle classes and charging scenarios as well as charging technologies for heavy-duty vehicles are explained (Chapter 2). The section on the grid integration of electrified heavy-duty vehicles highlights the status quo in 2023 as well as current research results, and provides an outlook on future developments (Chapter 3). In order to better understand the grid integration of electrified heavy-duty vehicles (N3 and M3), references to light commercial vehicles (N1, N2, M2) are made. The market research and implementation examples show that unidirectionally controlled and bidirectional vehicles as well as the charging infrastructure are already available on the market for vehicle classes N1 and N2, and controlled charging of electric buses is already being implemented in many European cities (Chapter 3.1). Meanwhile, the research of the Elektro-Mobil projects is focused on the unidirectionally controlled and bidirectional charging of heavy-duty vehicles of classes N3 and M3 using various charging systems (Chapter 3.2).

Finally, three recommendations for action are formulated on how the grid integration of heavy-duty vehicles can be supported. These recommendations are aimed at strengthening the competitiveness of Germany and Europe as business locations, taking on a pioneering role in the grid integration of heavy-duty vehicles, and thus accelerating the decarbonisation of the transport sector.

The developed recommendations for action are summarised below. The detailed version of the recommendations can be found in Chapter 4.

COMMON LANGUAGE AND CROSS-SECTORAL TERMS

In order to accelerate the grid integration of electric trucks, players from the energy and transport sectors must communicate with each other. A common language is needed to simplify cooperation. There should be a standardised understanding of commonly used terms.

All stakeholders should define terms before using them. Where possible, existing definitions should be used so that the existing discourse on the grid integration of commercial vehicles can be continued on a common knowledge basis. A common language also makes it easier for truck manufacturers, grid operators, transport companies and other stakeholders to formulate common priorities.

CLOSING KNOWLEDGE GAPS THROUGH TARGETED RESEARCH

Electromobility in the passenger car sector is several years ahead of the commercial vehicle sector in terms of development. This knowledge can accelerate the integration of commercial vehicles into the grid. At the same time, bidirectional charging is being researched in parallel for passenger cars and commercial vehicles.

Researchers from funding projects, industry and research should close knowledge gaps regarding the transferability of findings from the passenger car sector to the commercial vehicle sector (and vice versa, where possible). A well-founded global comparison of pioneering projects in the field of grid integration of EHDVs would also be helpful.

SHARING KNOWLEDGE AND COOPERATION ACROSS EUROPE

Different geographical regions have different research needs. Through coordination and targeted exchange, findings from different European countries can be transferred to others so that solutions are available for the entire spectrum of geographical and climatic conditions.

European communication and cooperation must be facilitated and optimised. Research results must be made available internationally. A coordinating body at the European level can support this process and promote the dissemination of research results.

EXECUTIVE SUMMARY

Der Schwerlastverkehr ist für rund ein Viertel der verkehrsbedingten CO_2-Emissionen verantwortlich, daher ist für das Erreichen der Klimaziele auch ein emissionsfreier Schwerlastverkehr nötig. Um die politischen Ziele einzuhalten, stellen Hersteller schwerer Nutzfahrzeuge bei einigen ihrer Modelle auf den batterieelektrischen Antrieb um. Batterieelektrische Lkw mit Gewichtsklassen bis 26 t zulässigem Gesamtgewicht und Reichweiten bis 300 km sind bereits marktreif und befinden sich bei mehreren Herstellern in der Serienproduktion. Mit diesen Fahrzeugen sind Anwendungsfälle wie die „letzte Meile" heutzutage bereits darstellbar und die verfügbaren Ladeleistungen sind ausreichend, um die Fahrzeuge über Nacht vollzuladen.

Erste Modelle bis 44 t zulässigem Gesamtgewicht und mit Reichweiten, die sich auch für den Langstreckentransport eignen, befinden sich mittlerweile ebenfalls in (Vor-)Serienproduktion. Diese Fahrzeuge benötigen jedoch höhere Ladeleistungen, um während der gesetzlich vorgeschriebenen Pausenzeiten genügend Energie zwischenladen zu können. Die nötige Schnellladeinfrastruktur mit Ladeleistungen von über 500 kW befindet sich jedoch noch in der Demonstrationsphase. Die Finalisierung des Megawatt Charging System (MCS) mit Ladeleistungen von über 1000 kW wird 2024 erwartet.

Neben dem Megawattladen sind weitere Technologien zur Elektrifizierung des Langstreckentransports denkbar. Die Projekte aus dem Programm „Elektro-Mobil" arbeiten an der Entwicklung dieser Technologien, zu welchen auch ein Batteriewechselsystem und elektrische Straßensysteme wie Oberleitungen und Induktionsspulen zählen. Die nötige Netzanschlussleistung kann durch die Steuerung einzelner Ladevorgänge begrenzt werden. Darüber hinaus können durch bidirektionales Laden von Nutzfahrzeugen mit ihren enormen Batteriekapazitäten zusätzliche Geschäftsmodelle – wie z. B. das Erbringen von Systemdienstleistungen – erschlossen werden.

In diesem Impulspapier formuliert die Begleitforschung des Förderprogramms „Elektro-Mobil" einen Sachstand zur Netzintegration von elektrifizierten schweren Nutzfahrzeugen. In den Grundlagen werden die Netzintegration, verschiedene Fahrzeugklassen und Ladeszenarien sowie Ladetechnologien für schwere Nutzfahrzeuge erläutert (Kapitel 2). Der Abschnitt zur Netzintegration elektrifizierter schwerer Nutzfahrzeuge beleuchtet den Status Quo im Jahr 2023 sowie aktuelle Forschungsergebnisse und gibt einen Ausblick auf zukünftige Entwicklungen (Kapitel 3). Um die Netzintegration elektrifizierter schwerer Nutzfahrzeuge (N3 und M3) besser zu verstehen, werden auch Bezüge zu den leichten Nutzfahrzeugen (N1, N2, M2) hergestellt. Während die Marktrecherche und Umsetzungsbeispiele zeigen, dass für die Fahrzeugklassen N1 und N2 bereits unidirektional gesteuerte und bidirektionale Fahrzeuge und Ladeinfrastruktur am Markt verfügbar sind und auch das gesteuerte Laden von E-Bussen bereits in vielen europäischen Städten umgesetzt wird (Kapitel 3.1), legen die Elektro-Mobil-Projekte mit ihrer Forschung einen Schwerpunkt auf das unidirektional gesteuerte und bidirektionale Laden von schweren Nutzfahrzeugen der Klassen N3 und M3 mit verschiedenen Ladesystemen (Kapitel 3.2).

Abschließend werden drei Handlungsempfehlungen formuliert, wie die Netzintegration von schweren Nutzfahrzeugen unterstützt werden kann. Diese Empfehlungen zielen darauf ab, die Wettbewerbsfähigkeit der Wirtschaftsstandorte Deutschland und Europa zu stärken, eine Vorreiterrolle bei der Netzintegration schwerer Nutzfahrzeuge einzunehmen und damit die Dekarbonisierung des Verkehrssektors zu beschleunigen.

Die erarbeiteten Handlungsempfehlungen werden im Folgenden zusammengefasst. Die ausführliche Version der Empfehlungen findet sich in Kapitel 4.

GEMEINSAME SPRACHE UND SEKTORÜBERGREIFENDE BEGRIFFE

Um die Netzintegration von E-Lkw voranzutreiben, müssen Akteur:innen aus den Sektoren Energie und Verkehr miteinander kommunizieren. Um die Zusammenarbeit zu vereinfachen, bedarf es einer gemeinsamen Sprache. Für gemeinsam verwendete Begriffe sollte es ein einheitliches Verständnis geben.

> Alle Akteur:innen sollten Begriffe definieren, bevor sie sie verwenden. Dabei sollte, wo möglich, auf bestehende Definitionen zurückgegriffen werden, damit der bestehende Diskurs rund um die Netzintegration von Nutzfahrzeugen auf einer gemeinsamen Wissensbasis weitergeführt werden kann. Eine gemeinsame Sprache erleichtert auch das Formulieren gemeinsamer Prioritäten von Lkw-Herstellern, Netzbetreibern, Transportunternehmen und weiteren Akteur:innen.

WISSENSLÜCKEN DURCH GEZIELTE FORSCHUNG SCHLIEßEN

Die Elektromobilität im Pkw-Bereich ist dem Nutzfahrzeugsektor bereits einige Jahre in der Entwicklung voraus. Diese Kenntnisse können die Netzintegration von Nutzfahrzeugen beschleunigen. Gleichzeitig wird das bidirektionale Laden bereits parallel bei Pkw und Nutzfahrzeugen erforscht.

> Forschende aus Förderprojekten, Industrie und Wissenschaft sollten Wissenslücken zur Übertragbarkeit von Erkenntnissen aus dem Pkw-Bereich auf den Lkw-Bereich (und gegebenenfalls vice versa) schließen. Ebenso wäre ein fundierter globaler Vergleich von Vorreiterprojekten aus dem Bereich der Netzintegration von schweren Nutzfahrzeugen hilfreich.

WISSEN TEILEN UND EUROPÄISCH KOOPERIEREN

Verschiedene geografische Regionen bedingen unterschiedliche Forschungsbedarfe. Durch Koordination und gezielten Austausch können Erkenntnisse aus verschiedenen europäischen Ländern in andere übertragen werden, sodass für das ganze Spektrum an geografischen und klimatischen Voraussetzungen Lösungen bereitstehen.

> Europäische Kommunikation und Kooperation müssen erleichtert und optimiert werden. Forschungsergebnisse müssen international verfügbar gemacht werden. Eine koordinierende Stelle auf europäischer Ebene kann diesen Prozess unterstützen und die Verbreitung der Forschungsergebnisse vorantreiben.

TABLE OF CONTENTS

1 INTRODUCTION

The European Green Deal envisages Europe becoming the first climate-neutral continent by 2050 and no longer producing net greenhouse gas emissions thereafter (Figure 1). On the way to this goal, emissions are to be reduced by 55% by 2030 compared to 1990 levels.[1] Achieving this milestone will require a significant decarbonisation of road transport, which was responsible for around 20% of the CO_2 emitted in the EU in 2020.[2] A large share of these emissions is attributable to the road-based passenger and freight transport sector. Although only accounting for 2% of vehicles on European roads in 2020,[3] heavy goods vehicles and buses caused 28% of transport-related CO_2 emissions in the EU, thus these vehicles are particularly important for achieving the emission targets.[2]

levels.[4] Therefore, the Climate Protection Programme 2030 by the German government stipulates that one third of road freight transport mileage should be electric or using electricity-based fuels by 2030.[5]

In the passenger car sector, the European market has already decided to switch to battery-electric drives and the transformation of the automotive industry is in full swing.[6] In heavy goods transport, too, there are indications that a large proportion of road freight transport will be battery-electric.[7] In 2020, Scania, Daimler Truck, Volvo Trucks, MAN, DAF and Ford signed a declaration of intent to only sell commercial vehicles that run without fossil fuels by 2040.[8] MAN and Daimler Truck have since announced that half of their vehicles sold in Europe are to be battery-electric by 2030,[9] while Volvo Trucks is aiming for half of all

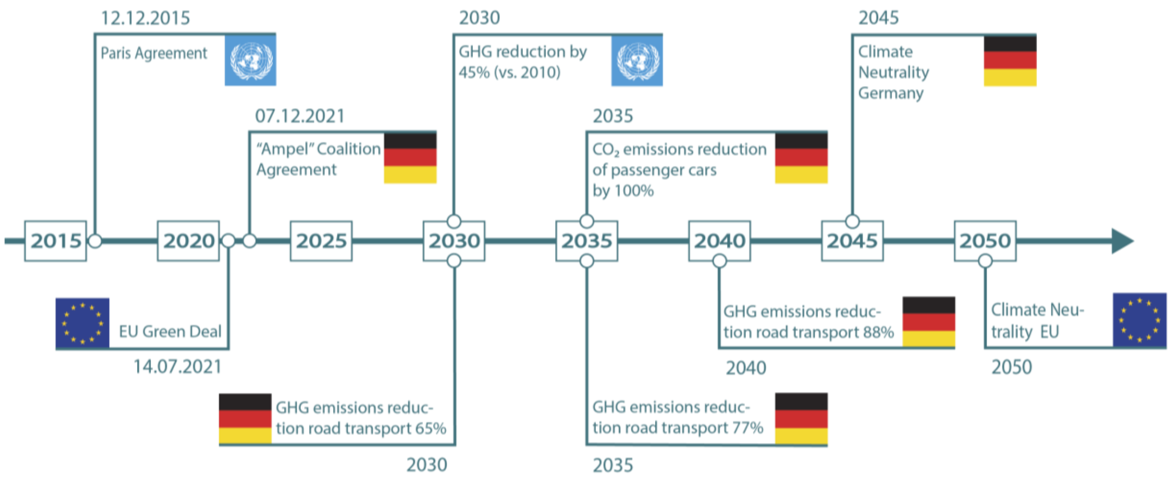

Figure 1: Some decarbonisation targets adopted by the United Nations, the European Union, and Germany.

Road freight transport plays a central role, especially for Germany as an industrialised country with a large export surplus, a central location in Europe, and a dense long-distance road network. As a leading industrialised nation, Germany has set itself even more ambitious CO_2 reduction targets than the EU. The current version of the Federal Climate Protection Act mandates that greenhouse gas emissions are to be reduced by 65% by 2030 compared to 1990

trucks sold worldwide to be battery-electric by 2030.[10] Both Scania and Volvo Trucks have shown the prospect of an all-electric portfolio by 2040.[11,12] An extensive survey among manufacturers of heavy-duty commercial vehicles, which together cover 95% of the market, has shown that they expect more than half of their vehicles sold in Germany to be battery-electric by 2030.[13]

However, the development of electric heavy-duty vehicles (EHDVs) themselves is only one of several aspects of the electrification of the transport sector, the required charging infrastructure being another. According to calculations, the majority of the charged energy will be obtained at the depot,[14,15] but beyond that, a public charging infrastructure must ensure that long-haul transport can be carried out with EHDVs in a manner comparable with or even offering advantages over diesel-powered vehicles. Due to long transport routes and widely branched supply chains, the development of a charging infrastructure for EHDVs is an inherently international issue. It must comply with international norms and standards in order to ensure comprehensive interoperability and user-friendliness. It is also advisable to simultaneously develop solutions to existing problems such as the lack of parking spaces for long-haul transport trucks. According to estimates by the German Road Haulage Logistics and Disposal Association (Bundesverband Straßengüterverkehr Logistik und Entsorgung, BGL), there is currently a shortage of between 35,000 and 40,000 parking spaces for trucks on German motorways alone.[16]

Due to the decision that only zero-emission vehicles are to be newly registered in the EU from 2035 in the passenger car and light commercial vehicle sectors, a strong increase in battery-electric vehicles (BEVs) is to be expected in these segments by 2050. To operate these vehicles, sufficient charging infrastructure must be available, which is supposed to be supplied with electricity from renewable sources.

The rise renewable energy is accompanied by both more decentralised generation and flexibilisation of consumption, giving rise to unprecedented interactions between the energy system and the industrial, building and transport sectors. Dedicated studies examine the interactions between transport sector and electricity grids, among other things.[17] For a successful energy transition, transmission and distribution grids need to be expanded.

Due to the size of the traction batteries in EHDVs and the amount of energy required to operate them, the impact of individual charging processes on the power grid is potentially greater than for individual cars. However, as with passenger cars, it is possible to control charging processes for EHDVs, although the possibilities and effects still need to be tested.

Successful grid integration of EHDVs and their large traction batteries can be achieved, for example, by shifting charging processes from times of high demand or low supply to times of low demand or high supply, if this is compatible with their primary function. Thus, peak loads can be limited, reducing the load on the electricity grid, and save electricity costs. Especially where routes and operating times are relatively fixed (e.g. in public transport), charging processes are easy to plan so that potential flexibilities can be utilised profitably. In addition, bidirectional charging allows the existing capacities of traction batteries to be used as buffer storage to optimise self-consumption, among other things.

In this impulse paper, we present the current status* of efforts to integrate EHDVs into the German electricity grid. To this end, in Chapter 2 we provide some basic terms relating to grid integration (controlled unidirectional charging, bidirectional charging, grid-serving, market-serving and system-serving), as these terms are often defined and understood differently among industry stakeholders. At the same time, we are defining the scope of this impulse paper by indicating which vehicle classes and charging technologies we are examining. Our focus is on HDVs, i.e. vehicle classes N2 and N3 for trucks and M2 and M3 for buses. In Chapter 3.1, we provide an overview of the solutions already available for the grid integration of EHDVs. Market activities currently focus on controlled charging for vehicle classes N1, N2 and M3, with bidirectional charging-capable charging infrastructure, light commercial vehicles and buses also available from 2023. Chapter 3.2 shows how projects from the Elektro-Mobil funding

* End of October 2023

programme are advancing the grid integration of EHDVs with their research. We also take a look at European and international activities in this area for better contextualisation. Chapter 3.3 provides an outlook on where the grid integration of EHDVs could lead in the future. Finally, in Chapter 4, we provide three recommendations for action to drive the grid integration of the commercial vehicle sector forward and thus accelerate its decarbonisation.

2 BASICS

The ramp-up of electromobility is creating a highly dynamic link between the transport and energy sectors. This interface brings together stakeholders from different areas who interpret terms differently. In order to use clear language, this chapter explains the terms used in this impulse paper. We also show the most important use cases and charging scenarios for EHDVs in order to clarify the special requirements for charging infrastructure for these vehicles. Additionally – in agreement with experts from the Elektro-Mobil funding programme – some basics of various technologies for the charging of EHDVs that are currently being researched are explained.

2.1 Grid integration

A comprehensive definition of "vehicle-grid integration" (VGI) includes any type of change in the time, location or speed of a (dis)charging process of an electric vehicle connected to the electricity grid with the aim of optimising the interaction of the vehicle with the electricity grid and generating benefits for the parties involved. This includes the use of the electric vehicle as a mobile energy storage device, the reduction of energy costs, the increased integration of renewable energy production, the provision of grid services and the reduction of grid expansion.[18]

The accompanying research Elektro-Mobil has published a white paper on the control of charging processes in the passenger car sector,[19] whereby the underlying communication channels are basically transferable to the HDV sector.[20] In this white paper, a distinction is made between uncontrolled charging, controlled unidirectional charging (V1G) and bidirectional charging (V2G or V2X). This classification is also used in this paper and is therefore taken up and defined in the following sub-chapters (Chapter 2.1.1 to Chapter 2.1.3). For the sake of completeness, we would like to point out that industry players use other terminology (e.g. charging management/V2G/participation in the regular market[21]) – these different classifications represent a hurdle for communication in the industry.

2.1.1 Uncontrolled charging

If no form of charging management is used, this is referred to as "uncontrolled charging". In this case, charging takes place immediately with the maximum power that is possible with the devices involved (vehicle and charging infrastructure) until the specified state of charge is reached. In this case, the maximum costs for the energy supply are incurred.

2.1.2 Controlled unidirectional charging

Controlled unidirectional charging" (also known as "intelligent charging" or "smart charging") is a charging process of an electric vehicle ("**v**ehicle" → V**1**G) that is postponed into the future or carried out with less than the technically possible maximum power due to a signal. For example, this can be a signal about the status of the electricity grid ("**g**rid" → V1**G**) in order to prevent a grid overload. If a dynamic electricity tariff is used, charging can be carried out at lower electricity prices by shifting a charging process from a period of high demand to a period of low demand, e.g. to a time when a higher supply of electricity from renewable sources is available. In this case, energy is always transferred from the power grid to the vehicle, i.e. in one direction only (**uni**directional → V1G).

2.1.3 Bidirectional charging

In contrast to unidirectional charging, bidirectional charging also allows energy to be drawn from the vehicle battery (bidirectional → V2X) in order to power an unspecified consumer (V2X). For example, this consumer may be located in a commercial or residential building on the same property as the charging point, and therefore behind the grid connection point from the view of the distribution system operator ("vehicle to building/business" → V2B or "vehicle to home" → V2H). The ability to feed electricity back into the grid ("vehicle to grid" → V2G) can contribute to system and grid stability and generate additional profit for the vehicle owner. For example, electricity can be purchased at favourable prices in times of high supply and fed back at higher prices when demand is high.

2.1.4 Flexibilities

The free energy storage capacities in the vehicle batteries can be used as flexibility for the electricity grid and support it in different ways. Utilisation is therefore often divided into three different types: grid-serving, market-serving, and system-serving. The optimised operational management of the electricity grids is fundamental for each type of flexibility use. In addition to these three, the terms "grid-friendly" or "grid-compatible" charging are also sometimes used, which are difficult to distinguish and which we will not discuss further here. In order to create a standardised understanding for this paper, we use the following definitions:

- *Grid-serving* use of flexibility can reduce grid costs. This includes the reduction of grid bottlenecks, the need to expand the grid and the optimised operation of the grid. The grid load can be reduced and grid expansion postponed or avoided through the knowledge, planning and controllability of flexibilities. For example, calling up flexibility to provide electricity behind a grid bottleneck can help to reduce the strain caused by the bottleneck. [22]
- *Market-serving* utilisation of flexibilities means that these are traded on the day-ahead or intraday market, thereby balancing supply and demand on the market. [23]
- *System-serving* flexibility is demanded by transmission system operators and traded on the balancing power and balancing labour market.[22]

2.2 Vehicle classes, use cases and charging scenarios for commercial vehicles

With around 6.3 million vehicles, commercial vehicles account for around 11% of all motor vehicles (cars and trucks combined) in Germany.[24] Due to their high total weight compared to passenger cars, commercial vehicles require larger traction batteries, especially for heavy goods traffic and long-haul transport. Due to their comparatively large batteries, yet simultaneously short standing and charging times, individual charging processes of heavy commercial vehicles can have a significantly greater impact on the power grid than those of passenger cars. The potential offered by controlled and bidirectional charging of these vehicles is correspondingly large.

Motor vehicles are divided into different weight classes in accordance with EU Directive 20007/46/EC. Table 1 provides an overview of vehicle class "N", motor vehicles with four wheels for the carriage of goods, and vehicles in class "M", buses and coaches for the carriage of passengers, for example for use in local public transport.[25,26] This impulse paper focuses specifically on vehicles in classes N2 and N3, as these require their own public charging infrastructure, which in turn places special demands on the electricity grid.

Commercial vehicles in these classes are generally developed for specific applications. In sub-sectors such as scheduled services within logistics networks or in local public transport, idle times, ranges and energy consumption can be determined in advance and the schedules planned accordingly. Specific charging scenarios are derived from the use cases, allowing the potential of controlled and bidirectional charging of different vehicles in the respective use cases to be derived qualitatively. The National Centre for Charging Infrastructure on behalf of the German Federal Ministry for Digital and Transport (BMDV) has summarised the most important charging scenarios for heavy commercial vehicles – including the heavier vehicles in class N2 and all vehicles in class N3 – as part of cleanroom discussions with industry representatives from truck manufacturers.[27] The 7 identified charging scenarios are divided into three non-publicly accessible charging scenarios (private company premises, e.g. depot, third-party company premises, mobile charging points), three publicly accessible charging scenarios (charging hubs in commercial centres, charging points in the public domain) and three publicly accessible charging scenarios (charging hubs in commercial areas, e.g. supplier parks or charging hubs on transport axes for night charging or intermediate charging during driving breaks) as well as a mixed charging scenario (transshipment points such as freight distribution centres). In the context of this impulse paper, we mainly differentiate between non-public charging (e.g. in depots) and public charging, whereby a distinction is made between fast charging (e.g. during the day on the motorway) and slow charging (e.g. for longer overnight stops).

The electrification of vehicle classes N2 and N3 is of great importance for the coming years in terms of climate policy and requires precise planning when setting up the necessary charging infrastructure. The charging scenarios described show that this infrastructure must be erected both publicly and privately, which requires cooperation between private players and public institutions. According to studies, between 55 and 90% of the energy will be obtained at non-public charging points, as electricity costs are lower there than at public charging points; moreover it is possible to incorporate in-house electricity production and stationary energy storage.[14,15] The remaining charging processes are carried out at public charging points. Due to this pronounced position of depot charging, a manual on the electrification of depots was created on behalf of the "Dutch National Charging Infrastructure Agenda".[28]

The identified charging scenarios (non-public depot charging, public slow night charging, public fast charging) present different challenges. Longer standing times and therefore also charging times in the depot are reduced by driving in shifts. In order to enable dozens of trucks to continue their journey after a 45-minute break using fast charging, very high connection capacities must be made available at highly frequented charging hubs.[29,30] The only widely available charging infrastructure to date is based on the CCS2/combo system. It is there assumed that a

Table 1: Vehicle classes in the commercial vehicle sector as well as possible use cases and charging scenarios.[25,31]

Vehicle class	Permissible total weight	Designation	Possible use cases	Possible charging scenarios
N1	< 3,5 t	Light commercial vehicle	Service and delivery ("last mile")	In own company (non-public)
N2	3,5 -12 t	Light truck Heavy truck	Delivery in local transport Delivery in regional transport, transport of volume goods	In own company; at business partner locations (non-public)
N3	> 12 t	Heavy truck Tractor unit	Part of an articulated train in long-distance freight transport Long-distance freight transport	Depot charging (non-public); on transport axes (public)
M2	< 5 t	Minibus	Passenger transport with at least 8 seats	Depot charging (non-public)
M3	> 5 t	Bus	Passenger transport with at least 8 seats	Depot charging (non-public)

conductive, plug-based fast charging infrastructure will emerge as the standard, but could be supplemented by complementary charging technologies. The requirements for a future charging infrastructure landscape are explained below and potential additions to stationary fast charging are outlined.

2.3 Charging technologies for EHDVs

The charging of EHDVs requires a well thought-out combination of needs-based charging infrastructure both in public spaces and on private property. The grid expansion required to supply this charging infrastructure depends on how much charging capacity is needed in the public charging infrastructure on the transport axes, how much is charged in private depots or at transshipment points, which charging technology is used, and how high the proportion of controlled charging is. The predictability of energy demand and charging capacity depends on how precisely fleet operators know their passenger and freight transport routes. The more fleet operators charges on their own premises, the better these fleets can be charged in a tariff-optimised manner and their own energy production can be integrated. Furthermore, the grid integration of EHDVs with their enormous battery capacities can open up additional business models. However, the prerequisite for providing system services or the grid-friendly control of charging processes, for example, is that the realisation of the primary function – i.e. the transport business – can continue without interruption.

In principle, several charging technologies are capable of supplying the large traction batteries of EHDVs with the required amounts of energy, although there are differences in the degree of maturity between the individual technologies. Various charging technologies are being researched in the projects of the Elektro-Mobil funding programme and it is being investigated how they can complement each other synergistically. These technologies have similar overall energy efficiencies and therefore energy requirements. However, the different charging technologies give rise to different spatial and temporal concentrations of charging processes, resulting in different requirements for the number of charging locations and their respective grid connection capacities. There are also technology-specific options for controlling charging processes and bidirectional charging in order to support the electricity grid.

Regardless of the charging technology, the transport business has top priority. Availability and reliability of the charging infrastructure are essential for an economically orientated organisation. For use cases that require a public charging infrastructure, the most important conditions are the possibility to reserve a parking spot including a charging point and power, interoperability (across countries and brands), user-friendliness and high reliability as well as fast repair in the event of a problem. In addition to these aspects, another prerequisite for the switch to electric vehicles from the user's perspective is cost parity with diesel vehicles. Beyond the technical requirements, human needs must also be taken into account, including sanitary facilities, gastronomy, weather protection, noise protection, and safety. It should also be borne in mind that many transport companies operate across borders; therefore it makes sense to plan the development of charging infrastructure for commercial vehicle transport at a European level.

2.3.1 Electric Road Systems

Hybrid systems comprising overhead lines and diesel engines have been under development for long-haul heavy goods transport for around 15 years.[32] Three multi-year field trials have already been performed in Germany to test EHDVs on overhead catenary lines under real-world conditions.[33] The field of overhead contact lines can not only draw on 100 years of experience from rail-bound transport systems, there is also a global industry with established supply chains and production capacities with an annual revenue of approximately 10 billion euros.[34]

An electric truck that is connected to an overhead line via a pantograph while driving can continuously feed its electric motor directly from the electricity grid.[35] In addition to directly supplying the motor for locomotion, the pantograph also enables dynamic charging of the traction battery while travelling as well as stationary charging. This makes it possible to decouple the resting and charging locations as to not further exacerbate the shortage of parking spots. The biggest advantage of a battery electric truck outfitted with a pantograph is the ability to install a smaller traction battery than a truck that has to be able to cover long distances without continuous charging. As the traction battery accounts for around 50% of the price of a truck,[36] overhead line trucks offer cost advantages over other charging technologies. At the same time, the vehicle is lighter and consumes less energy, which means that operating costs are also lower. In addition, continuous charging during the journey at low charging power protects the installed battery. On the other hand, vehicles with smaller batteries are more dependent on a dense charging infrastructure, as they can only cover shorter distances away from the overhead line. According to a study from 2020, the calculated length of an overhead line network in Germany is around 4000 km when completed, and is estimated to cost around 12 billion euros to roll out.[37]

The spatial distribution of the substations required for the overhead line infrastructure along the motorway would enable a highly decentralised connection to the electricity grid, avoiding the construction of large grid connections and the lengthy approval procedures that precede them. Furthermore, the load would be distributed more evenly across the electricity grids during operation than in the case of fewer but larger grid connections. On the other hand, it would be necessary to create many small grid connections and lay the lines along the motorway, which would require access to many properties and their respective owners. If distribution to several small grid connections in a region is not possible, the necessary power can also be brought to the motorway via fewer, larger power lines from medium or high-voltage grids. In this case, a medium-voltage power line could be carried along sections of motorway with the overhead line infrastructure.

In principle, it is possible to integrate a pantograph into any electric vehicle with a different charging technology. Directly supplying the electric motor allows to bypass the traction battery, reducing battery ageing and avoiding conversion processes, which increases energy efficiency. However, the installation of the pantograph system causes additional weight in the vehicle, additional complexity in production and correspondingly higher purchase costs.

During dynamic charging on an overhead line, controlled charging (V1G) cannot generally be employed because the drawn energy is used directly to operate the electric motor. When the battery is full, excess energy generated by recuperation could be fed back into the power grid (V2G), but the energy quantities would be small. During static charging via pantograph (e.g. in the depot), V1G or V2G could be implemented more easily, but the low capacity of the installed traction battery offers relatively little scope for such applications.

An alternative electric road system for long-distance transport is based on wireless power transfer via induction. The advantages and disadvantages for the energy system and the users are basically the same as those of the overhead contact line. However, a contactless system could also be used by passenger cars, provided that interoperability and a billing system for the transmitted energy are available. Rolling out the wireless charging infrastructure over a large area is considered to be very time-consuming and cost-intensive, as the energy-transmitting coils are embedded in the road, and a roll-out would require a temporary interruption of traffic in the relevant lane. If the charging infrastructure is to be used primarily by EHDVs, the roll-out could be combined with the maintenance cycles of the right-hand motorway lane, which wears out most quickly due to heavy goods transport traffic. However, a roll-out in this manner would take a long time. Overall, inductive charging for long-distance transport is still at a very early stage of development. Accordingly, there are no long-term experiences of the durability of an energy supply infrastructure integrated into long-distance roads, thus the costs and risks of the technology are difficult to reliably quantify at present.

2.3.2 Megawatt charging

A range of 400 km is theoretically sufficient to cover daily distances of 700-800 km, provided that a full traction battery is available after a break from driving. The Charging Interface Initiative e.V. (CharIN) has been driving the development of the Megawatt Charging System (MCS) since 2018, which is designed to ultimately enable charging powers of up to 3.75 MW (3000 A at 1250 V).[38] The first major milestone are charging capacities of up to 1 MW, which will be sufficient in the eyes of most e-truck manufacturers.[13]

However, EHDVs with a gross vehicle weight of up to 44 t and ranges of 500 to 800 km are already in (pre–)serial production,[39,40,41] which means that longer trips than 400 km are also possible with-out intermediate charging. In this case, the lawfully mandated rest periods also apply, but a parking spot with charging facilities is not necessarily required, which means that the shortage of parking spaces is not further exacerbated. In addition, longer ranges also make it possible to travel to areas with less developed charging infrastructure. To enable these long ranges, traction batteries of appropriate sizes are required, which equally increases the demand for raw materials for the active battery components. For example, truck manufacturer Designwerk puts the weight of its 1000 kWh battery at 5620 kg.[42,43] An increased battery capacity means an increase in purchase price as well as vehicle weight, which also increases the average consumption and reduces the energy efficiency of the vehicle.

Truck manufacturers are already laying out the battery capacities of their long-haul vehicles to have ranges of 400-500 km.[44,45,46] Thus, journeys between charging points can be carried out conveniently without having to carry disproportionately heavy batteries and incur efficiency losses. However, vehicles with longer ranges could be better utilised in regions where fast charging infrastructure cannot be operated economically, e.g. in areas with low population density or low transport traffic volumes.

To provide the necessary charging power for megawatt charging parks, connections to the medium- or high-voltage grids are required. The authors of two studies commissioned by Transport & Environment (T&E) and the German National Charging Infrastructure Control Centre have calculated a required grid connection capacity of approximately 60 MW for both directions of travel combined for a typical logistics hub, which would necessitate a connection directly to the high-voltage grid.[29,30] This high local and temporal concentration of power demand is comparable in size to a city with 75,000 inhabitants[47] and represents a major challenge for the electricity grid. In the HoLa project, the most lucrative locations for such charging parks in Germany were identified based on real GPS data and presented on an interactive website.[48] The authors of another study by T&E estimate that, in order to achieve the climate targets, a comprehensive network of conductive charging infrastructure for long-distance freight transport along the TEN-T transport routes in Europe will require around 6600 public high-power charging points and 4400 non-public charging points by 2030, at a total cost of around 1.9 billion euros.[49]

Due to the high time pressure in the transport sector, it can be assumed that V2X applications will hardly be possible in charging scenarios during the day on the motorway or during loading/unloading stops with currently available battery sizes and charging speeds, as the vehicles must be ready to continue their journey after a short standstill. Controlled charging can be used, however, as traction batteries are not usually charged at full power over the entire range from 0-100%. In addition, depending on the state of charge and the remaining dwell time of other electric vehicles in the same charging park, it is possible to prioritise which vehicles require higher charging power than others. However, both controlled charging and V2X applications are conceivable during longer downtimes, such as overnight charging on the motorway or during the weekend in the depot. In particular, the possibility of controlling charging processes should be taken into account when designing the grid connection of depots and overnight car parks in order to reduce costs and minimise the construction effort.[28]

2.3.3 Battery swapping systems

EHDVs in long-distance transport could also regain their full range by replacing the (partially) empty traction batteries with fully charged ones. Between 2017 and 2020, the Federal Ministry of Economics and Technology funded a project in which a truck was converted to an electric drive train and equipped with traction batteries that could be changed manually using a forklift truck in less than 15 minutes.[50] A fully automatic battery swapping system (BSS) for EHDVs with changing times of just a few minutes is currently under development as part of a project in the Elektro-Mobil funding programme.[51]

The additional space requirement of a BSS is less than that of a megawatt charging infrastructure, as the driving break after the battery change can be spent at any parking space. The raw material requirement of a BSS is generally higher since swapping batteries must be kept in stock in addition to the batteries in the vehicles themselves. However, through uni-directionally controlled charging, the stored batteries can be charged in a manner both more grid-friendly and battery-friendly, which increases their lifespan. The stored batteries can even have a secondary use as stationary storage, which means that less energy storage is required elsewhere. As the batteries are not in the vehicle in this case, it is therefore not strictly correct to speak of V2X. Nevertheless, the flexibility available in the stored batteries through bidirectional charging could also enable additional business models for the operators of battery swap stations. In Denmark, this type of use of swapping batteries from the passenger car sector for frequency control is already being trialled.[52]

EHDVs with ranges suitable for use in long-distance transport can be supplied with sufficient energy for the next leg of the journey during breaks via both BSS and MCS. Due to compatible battery sizes, battery swapping and megawatt charging could complement each other synergistically. If both technologies are installed in a vehicle, electricity can be drawn from either charging infrastructure, though having two charging systems on board increases the complexity of vehicle production. Which charging infrastructure is installed at a given location can be decided on the basis of local conditions such as pre-existing grid connection and availability of space. An EHDV with battery swap capability could also be equipped with an additional pantograph system but would also gain production complexity and weight.

There are no publicly available projections for the costs of an initial network of battery swap stations in Germany yet. There is currently no market for battery swap systems for trucks in Germany or Europe, while around 18,000 battery swap-capable electric trucks were sold in China alone in 2022.[53] These are mainly used in applications with compara-tively short one-way distances of less than 100 km, such as in ports, raw materials companies, and city logistics.

3 GRID INTEGRATION OF ELECTRIFIED HEAVY COMMERCIAL VEHICLES

The electrification of the commercial vehicle sector is already in full swing in vehicle classes N1 and N2 – measured by the increasing number of available models (see Chapter 3.1.1) – as well as vehicle classes M2 and M3 – measured by the increasing number of buses in operation (see Chapter 3.1.2). Accordingly, solutions for the grid integration of these vehicle classes are already being implemented, examples of which are presented in Chapter 3.1.[54,55] In addition, it is shown that electric vehicles of the N3 class are used on routes up to 300 km and are also charged in a controlled manner. The emerging market for electric N3 vehicles for longer distances is expected to grow steadily,[56,57] and Chapter 3.2 describes the current research activities to integrate these vehicles into the grid. Based on information from workshops and knowledge exchanges, an outlook on which aspects of the grid integration of EHDVs have not yet been sufficiently researched and should be investigated in the future is provided in Chapter 3.3.

Chapter 3 also provides an overview of the solutions for integrating electric commercial vehicles into the grid that are currently available on the market and which solutions are still under development. Due to the large number of implementation projects, pilot tests and research projects, there is no claim to completeness. It should also be noted that developments on the market are very dynamic at present. This chapter is based on information that was available until the end of October 2023; later information has not been taken into account.

3.1 Status quo 2023

Market research and implementation examples show that in the case of electric trucks, grid integration mainly takes place in vehicle classes N1 and N2, using unidirectionally controlled charging. The first products and examples for bidirectional charging of N1 and N2 vehicles on the one hand and for unidirectionally controlled charging of N3 vehicles on the other hand are recognisable. Only one N3 vehicle manufacturer currently offers an EHDV capable of bidirectional charging, which is not yet available with any standard charging infrastructure. The application examples focus on non-public charging scenarios.

The grid integration of heavy electric buses is well advanced already and there are many examples of controlled charging of M3 buses. In 2023, several providers offer bidirectional charging infrastructure for electric buses, which can be used for both non-public charging in depots and for fast charging in public areas.

For both electric trucks and buses, conductive charging technology is used, but not yet in the megawatt range.

3.1.1 Trucks (N1-N3)

The number of purely electrically powered models in the N1 and N2 vehicle classes has risen steadily in recent years. Vehicle manufacturers offering light commercial EVs include Citroën, Fiat, Ford, Opel, Mercedes-Benz, Nissan, Peugeot, Renault, Toyota and VW.[58,59] Although the development of heavy-duty electric vehicles in the N3 class is still in its relatively early stages, several models are already available and will soon be joined by others (see Appendix 1 Table Market overview of electric trucks). With the current technology, ranges of up to 300 km can be achieved in all weight classes permitted on German roads (up to 44 t gross vehicle weight). For high payloads and ranges of over 500 km, battery sizes of over 600 kWh are required. The fast-charging capacities of standard models usually range between 100 and 400 kW, but the first models are already designed for megawatt charging.

Unidirectional charging is standard equipment today. As the CHAdeMO standard mainly used by Japanese vehicle manufacturers was designed for bidirectional charging at an early stage, in 2021 the only vehicles in the N1 class capable of bidirectional charging were produced by Japanese manufacturers (e.g. Nissan), but these models were not widespread in Europe.[60] Since 2022, Ford has been offering the F-150 Lightning, an electric light commercial vehicle that can charge tools, for example, and supply entire households with electricity via bidirectional charging using a CCS plug, provided they are used with the appropriate hardware from Ford.[61] The Ford E-Transit Custom can also charge bidirectionally and supply devices with up to 2.3 kW.[62] VW has been offering the ID. Buzz with a CCS2 plug capable of bidirectional charging.[63] In the N2 and N3 classes, only MAN currently offers an electric commercial vehicle with bidirectional charging capability.

So far, 27 wallboxes and charging stations have been announced that are about to be launched, are said to enable V2X, and are produced in series (21 DC, 3 AC, 3 unknown; see Appendix 2 Table Market overview of charging infrastructure).[64] Only a few products can be purchased directly at present (end of 2023), but there is a pre-order option for many bidirectional wallboxes and charging stations. The outputs of these charging stations range from 10-25 kW and are more suitable for charging light commercial vehicles. While light commercial vehicles, such as the VW ID. Buzz, can be charged with 11 kW AC (and up to 170 kW at a DC fast charger),[65] electric trucks require higher charging capacities for long-haul transport. Fast charging stations available on the market offer charging capacities between 350 and 480 kW, e.g. from Tesla,[66] Ekoenergetyka,[67] Tritium,[68] ABB,[69] Elexon,[70] Alpitronic[71] and Kempower[72] and are currently not V2X-capable as standard (see Table **2**).

According to Measure 61 of the Charging Infrastructure Masterplan II, a concept for the development of an initial, scalable charging infrastructure network for heavy goods transport along the long-distance transport network in Germany was to be drawn up by Q1/2023.[73] However, the invitation to tender for this charging network, which was planned in Measure 62 of the same document by Q3/2023, had not yet taken place by the end of 2023.[74]

One company that has already started planning and building a dedicated charging infrastructure for EHDVs is a joint venture between Volvo Trucks, Daimler Truck and Traton SE, which in turn includes manufacturers such as Scania and MAN. The aim of this joint venture, called Milence, is to set up fast charging parks throughout Europe by 2027 with at least 1,700 charging points with charging capacities of between 300 and 1,000 kW and enough space to park truck-trailer combinations.[75] In addition, Aral has already partially commissioned a 600 km long fast-charging corridor within Germany, the first stage of which will include 32 charging points with charging capacities of up to 300 kW and is also designed for electric trucks.[76] In Sweden, work is also underway on a nationwide fast charging network for electric trucks. Charging station operator Nimbnet, hardware manufacturer Kempower and infrastructure service provider Vitra are planning to start operating the first truck charging points in Gothenburg, Söderhamn, Sundsvall and Nordmaling, where electric trucks can be charged with up to 350 kW via CCS2 connections upon reservation by the end of 2023.[77]

The Deutsche Post DHL Group serves as a current application example for electric commercial vehicles in Germany with a fleet of 21,500 electric vehicles that are charged in a controlled manner at more than 27,500 non-public charging points at depots. In the N1 vehicle class, the company currently has a share

Table 2: Fast charging stations for electric trucks available on the market.

Provider	Name	Charging power (max.)	AC/DC	Plug
Tesla	Supercharger V4	350 kW	DC	CCS2
Ekoenergetyka	SAT 600 HPC	350 kW	DC	CCS2
Tritium	PK350	350 kW	DC	CCS2/CHAdeMO
ABB	Terra 360	360 kW	DC	CCS2/CHAdeMO
Alpitronic	HYC 400	400 kW	DC	CCS2/CHAdeMO
Kempower	Satellite	400 kW	DC	CCS2/CHAdeMO
Elexon	sxHPC480	480 kW	DC	CCS2

of around 25% electric commercial vehicles and is aiming for a share of over 38.5% by 2025. In the classes N2 and N3, around 18% of vehicles are electrified. Vehicle models used in Germany are StreetScooter,[78] Mercedes-Benz eVito,[79] Ford E-Transit,[80] Iveco eDaily,[81] Volvo FL Electric[82] and others. Charging processes are controlled nationwide via a cloud. Among other things, peak shaving, charging at low spot market prices and optimisation of self-consumption are achieved.[83,84] Deutsche Post DHL is also testing the dynamic charging of an EHDV by Scania on overhead lines in Germany.[85]

Further examples of the early acceptance of heavy electric trucks can be found at Österreichische Post AG[86] as well as the haulage company Falkenklev Logistik[87,88] and the logistics company Einride[89] in Sweden, all of which are in the process of expanding their electric fleets. Electric trucks from Volvo Trucks, Scania, DAF and Daimler Truck in the weight classes between 16 and 64 t (in combined transport in Sweden) are in use there. These vehicles are charged at charging infrastructure from Elexon, Ekoenergetyka and Kempower with up to 250 kW, and their ranges vary between 150 and 300 kilometres. The charging locations are depots, logistics terminals and charging hubs. The charging processes are controlled by charging and energy management system ChargePilot from The Mobility House[90,91] and the softwares ChargEye and Saga from Kempower[92] and Einride,[93,94] respectively.

3.1.2 Buses (M2-M3)

In 2022, there were already around 1600 battery-electric buses of the M3 vehicle class on the road in Germany, and the trend is rising.[95] In 2021, there were only around 1100 battery-electric buses.[96] The manufacturers of these electric buses include Mercedes-Benz, Solaris, VDL, MAN, Ebusco and BYD. An estimated 8500 electric buses (including hybrid, trolley and fuel cell buses) were driving on European roads in 2021.[97] Corresponding charging infrastructure for bus depots from Kempower,[98] ABB,[99] Heliox,[100] Jema Energy,[101] Hitachi Energy,[102] Ekoenergetyka,[103] Siemens,[104] and Schunk[105] is already in use at various locations.

Some of the electric buses already in use in public transport in the EU are charged using controlled DC fast charging via CCS2 from charging and energy management systems. The electric buses are already in operation in various European cities, e.g. Aalborg (Denmark),[106,107] Amsterdam (Netherlands),[108] Milan (Italy),[109] Aveiro (Portugal),[110] and Zaragoza (Spain).[111] The charging processes are controlled via the softwares ChargEye (Kempower), ChargePilot (The Mobility House), DepotFinity (Siemens), Grid-eMotionTM Fleet (Hitachi) or the Smart Charging Intelligent Management Platform (Enel X). By controlling each depot (i.e. non-publicly accessible charging infrastructure), annual savings of up to 100,000 euros can be realised (see the example of Amsterdam's public transport authority) through peak load shaving through unidirectionally controlled and tariff-optimised charging. According to The Mobility House, over 10% of the European bus market is being charged using its own charging and energy management system.[112] As recently as 2022, the same company said in its white paper titled "Elektrobusse intelligent laden" that in the future, it will be possible to feed energy from the batteries of electric vehicles back into the energy system.[113] eMIS has been offering a bidirectional charging infrastructure for electric bus fleets since 2023, enabling participation in the primary control power market as well as arbitrage transactions.[114,115] Jema Energy offers modular and interoperable chargers for bus depots as well as fast charging stations for opportunity charging, which can also feed back bidirectionally with low charging power.[116] In 2023, Ebusco presented its product "Ebusco Energy Flex", which is a mobile storage and charging solution capable of bidirectional charging in order to store excess energy and make it available for charging cars and buses on demand. [117]

Other large markets for electrified buses are in China, India and North America. Globally, most electric buses in 2022 were in China, with a share of

95%. The world's largest electric bus fleet with more than 16,000 vehicles is located in Shenzhen.[113]

In the USA, school buses make up the largest part of the public transport system. In 2022, less than 1% of the 480,000 buses were electrically powered, but since 2021, the Infrastructure Investment and Jobs Act has provided 2.5 billion US dollars for the purchase of new electric school buses. The benefits of integrating electric school buses into the grid are considered to be high (further information in Chapter 3.2.2).[118] The possibility of feeding energy back into the grid from bus fleets is particularly interesting in the USA because the power grids there are regularly overloaded or damaged by extreme weather events. Depending on the type of crisis, school buses sometimes cannot operate during this time in the first place (e.g. in extreme heat or cold) and could instead be made available to support the grid. At the same time, the revenue potential during these times is very high, which makes secondary utilisation of the fleets lucrative. The company Nuvve already offers a complete package for charging infrastructure solutions for the bidirectional charging of school buses, including V2G control software.[119]

3.2 Research in the Elektro-Mobil funding programme

The projects in the Elektro-Mobil funding programme are driving research in the field of grid integration of heavy goods transport in various areas.** At the time of writing, 15 projects with a focus on EHDVs were being funded in the programme. A more detailed overview of the activities of these projects can be found in Appendix 3.

** This impulse paper focuses on the Elektro-Mobil programme. As part of the "Directive on a joint funding initiative to promote research and development in the field of electromobility" (22.02.2021), there are also further research activities on heavy commercial vehicles and buses in the "Erneuerbar Mobil" programme.

There are 12 projects in the programme that deal with electric trucks and the respective charging infrastructure while 6 projects deal with electric buses and the respective charging infrastructure. All 12 truck projects are researching vehicle class N3, 4 of these projects are also looking at N2 vehicles and 2 projects are considering vehicle class N1. All 6 bus projects are researching vehicle class M3, 1 project is also looking at vehicle class M2. Thus, the vast majority of Elektro-Mobil projects in the commercial vehicle sector are working on heavy vehicles (N3 and M3) and the focus is more on trucks than on buses (see Figure **2**). This result is in line with the findings from Chapter 3.1, which showed that unidirectionally controlled and bidirectionally chargeable vehicles and charging infrastructure are already available on the market for vehicle classes N1 and N2, and that controlled charging of electric buses is already being implemented in many European cities. The Elektro-Mobil projects are therefore starting their research where off-the-shelf solutions stop.

In the described research projects, grid integration of commercially used EVs through unidirectionally controlled charging has already become established. However, many projects are now also looking at bidirectional charging. Non-public and public charging infrastructure are considered equally (in contrast to the application examples that focus on non-public charging infrastructure, see Chapter 3.1). The entire spectrum from V2H to V2B to V2G is analysed.

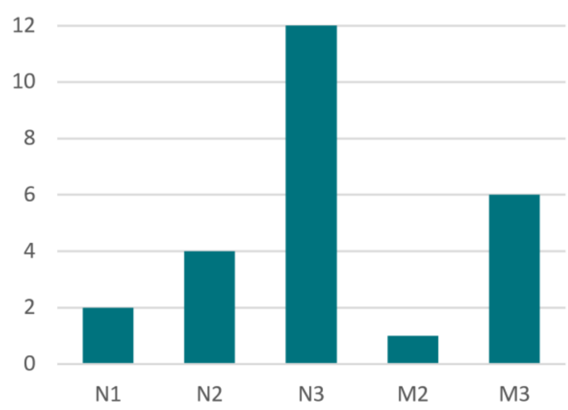

Figure 2: Frequency of the commercial vehicle classes considered in the Elektro-Mobil programme.

In addition to conductive charging, Electric Road Systems (ERS) are also being investigated for both electric trucks and buses, and a battery swap system (BSS) for electric trucks is also being developed. The research goes beyond what is available on the market by developing and testing charging technology in the megawatt range.

Chapter 3.2.1 first takes a closer look at the 12 Elektro-Mobil projects that focus on N3 trucks. Chapter 3.2.2 then looks at the 6 projects focussing on electric buses. For reference, research activities at EU level are also mentioned in both chapters.

3.2.1 Trucks (N1-N3)

Activities at national level in Elektro-Mobil

Characteristic of the funding programme Elektro-Mobil is its openness with regard to the researched charging technologies. Of the projects dealing with N3 vehicles, 8 projects are working with megawatt charging and 3 projects each are researching overhead line charging, inductive charging, and battery swapping (see Figure 3). As described in Chapter 2.3.1, both overhead line and induction systems are electric road systems (ERS). In terms of grid integration, ERS are interesting because the power required for charging is distributed spatially instead of generating local load peaks.

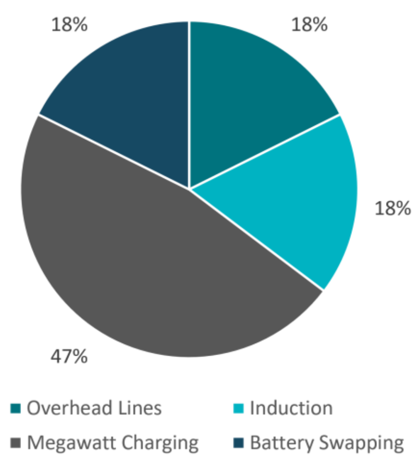

Figure 3: Charging technologies researched by the electric truck projects in Elektro-Mobil.

The **AMELIE 2** project (research type: simulation / demonstration) deals with the question of how overhead line systems can be implemented in the road network in technical, legal and organisational terms and how ERS can be integrated into existing energy industry and motorway structures.[120] The **E|MPOWER** project demonstrates how EHDVs can be charged while driving using inductive charging technologies on an electrified section of motorway (research type: demonstration).[121]

In the **eHaul** and **UniSwapHD** projects, a fully automatic battery swapping system for electric trucks is being developed (both - research type: simulation / demonstration) and tested on the route between Berlin and Dresden under real-world conditions.[51] While the prototype swapping system is being developed in the eHaul project, the employees in the UniSwapHD project have set themselves the goal of providing answers to the questions of standardisation of swappable traction batteries in the heavy goods transport sector. The two projects are planning to use the stored swapping batteries as stationary storage units to demonstrate the provision of grid services via bidirectional charging.[122]

The enERSyn project looks at the interface between the energy and transport sectors (research type: study / simulation). This is done by quantitatively analysing the interactions of different charging technologies with the energy system, with a particular focus on ERS concepts. The potential benefits of market-driven and possibly bidirectional charging will also be quantified. The enERSyn project considers BSS as well and is therefore one of the 3 projects dealing with this topic.[123]

The **eVTrailer2** project focuses on the electrification of trailers with the aim of enabling bidirectional HPC (high power charging) of trailers using a high-voltage box with charge controller and the developed battery system (research type: demonstration). This involves working on charging with high power at charging points or on overhead lines.[124]

Both enERSyn and eVTrailer2 – as well as the six following projects – deal with charging infrastructure

Project	Charging type		Charging technology			Connec-tion type		Vehicle class			Charging scenario		Type of research			Use Cases												
	Controlled unidirectional	Bidirectional	Battery change	Megawatt charging / CCS2	Electric Road System	Conductive	Inductive	N1	N2	N3	Non-public	Public	Study	Simulation	Development / Demonstration	V2H Self-consumption optimisation	V2H Tariff-optimised charging	V2B Peak shaving	V2B Fleet management	V2G Time-based arbitrage (intraday)	V2G Time-based arbitrage (day-ahead)	V2G Primary control power	V2G Local grid service	V2G Redispatch	V2G Reactive power provision	V2G Genuine green electricity	Emergency power supply	Powerbox
AMELIE 2	■				■	■			■	■		■		■	■													
E|MPOWER	■				■		■	■	■	■					■													
eHaul	■	■	■							■	■	■		■	■		■	■	■									
ELMAR	■	■		■		■				■	■				■	■	■	■	■							■		
enERSyn	■	■	■	■	■	■	■			■	■	■	■	■		■		■										
eVTrailer2	■	■		■	■	■	■			■	■	■			■			■	■				■					
HV-MELA-BAT	■	■		■		■				■	■				■			■										
IDEAL	■	■		■		■				■	■	■	■	■	■								■		■			
MEGA-LADEN	■			■		■		■	■	■	■	■			■													
NEFTON	■	■		■		■				■	■	■		■	■	■	■	■		■	■							
SPIRIT-E	■	■		■		■				■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■		
UniSwapHD	■	■	■							■	■	■		■	■		■	■	■									

Figure 4: Overview of the e-truck projects in Elektro-Mobil in terms of charging technology, type of connection, vehicle class under consideration, charging scenario, type of research and use cases in terms of grid integration.

for fast charging in the megawatt range. The **IDEAL** project, which is researching innovative DC technologies for the sustainable integration of modern charging infrastructure, is developing a fast and high-performance charging system for commercial transport and heavy goods vehicles (research type: study / simulation / demonstration).[125] A simulation model will be used to research the cost optimisation potential of both unidirectional and bidirectional charging. Similarly, **MEGA-LADEN** is developing a fully automated underfloor contact system for the depot charging of electric trucks in the megawatt range (research type: demonstration).[126] To that end, a unidirectionally controlled multipoint charging management system is to be trialled. The **HV-MELA-BAT** project team is building and testing a high-voltage megawatt charging system for high-performance charging in battery-powered heavy goods and passenger transport (research type: demonstration). A buffer storage system that can bidirectionally feed back into the power grid will be used as well.[127] The **NEFTON** project is investigating the feasibility and economic viability of fast-charging infrastructure concepts (research type: simulation / demonstration). Taking into account the requirements of vehicles and users, bidirectional power electronics for the charging infrastructure are being developed which should be able to provide balancing power and shave load peaks with the help of the vehicle battery or a buffer battery.[128]

In order to shorten the amortisation period of private charging infrastructure, efforts are being made to offer charging points in depots for external parties (e.g. with the help of reservation systems). The **SPIRIT-E** project (research type: simulation / demonstration) is working on the development of market-ready solutions for such "shared depots" for EHDVs. Based on real data, including validation through field trials, the consortium is carrying out profitability calculations for secondary energy industry use cases in the form of simulative studies. This also includes a field test for the bidirectional charging of electric trucks and their system integration at the logistics site. [129]

The **ELMAR** project is working on a special use case in which the participants are looking at the use of EHDVs in the raw materials industry (research type: demonstration). As raw materials companies are particularly energy-intensive, strategies are to be developed on the basis of the data collected and the resulting findings in order to facilitate the entry into electromobility for the entire industry. Controlled charging of transport vehicles and the possible use of buffer batteries will avoid peak loads and limit the required grid connection power. [130]

Figure 4 shows the electric truck projects in Elektro-Mobil with regard to the vehicle classes, charging types, charging technologies, charging scenarios, research types and use cases in terms of grid integration. Of the 12 truck projects, 10 projects each are conducting research into non-public and public charging scenarios. AMELIE 2 and E|MPOWER focus on ERS and thus exclusively on public charging, while ELMAR and HV-MELA-BAT are exclusively looking at non-public charging. All other projects consider both charging scenarios. All in all, the Elektro-Mobil projects takes a relatively balanced view at non-public and public charging scenarios for electric trucks. More recent projects even consider aspects such as shared depot charging infrastructure, i.e. charging infrastructure that is actually defined as non-public but can be opened up to third parties under certain conditions. Of the 12 projects that deal with electric trucks, all are researching unidirectional controlled charging and 9 of these projects are also researching bidirectional charging.

The projects were asked which use cases (according to the definitions of the use cases formulated in the BDL funding project final report[131]) were considered in the respective project. As shown in Figure **5**, the three most common use cases in the electric truck projects of Elektro-Mobil are **V2B peak load shaving** (8 projects: eHaul, ELMAR, enERSyn, HV-MELA-BAT, eVTrailer2, NEFTON, SPIRIT-E, UniSwapHD), **V2B fleet management** (6 projects: eHaul, ELMAR, KoLa, eVTrailer2, SPIRIT-E, UniSwapHD) and **V2H tariff-**

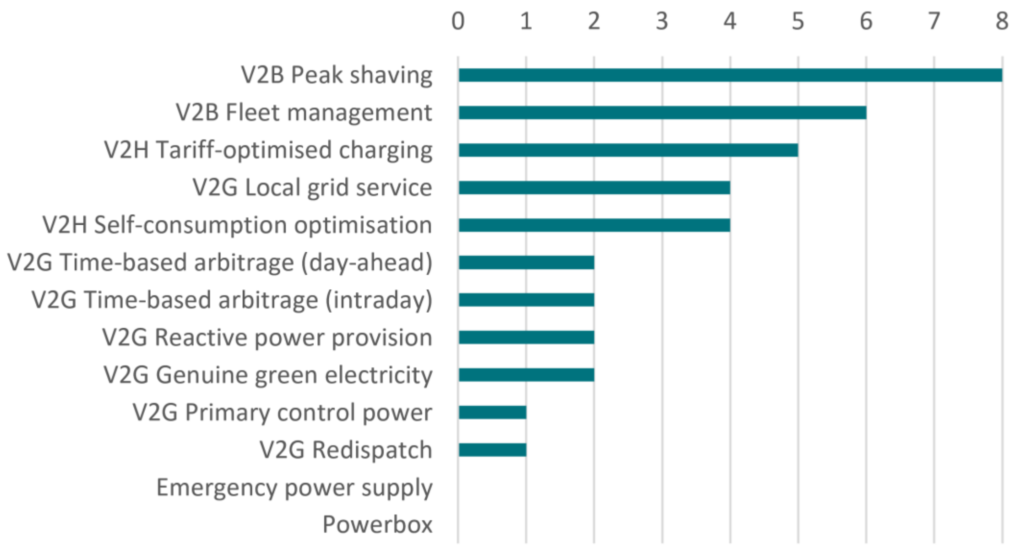

Figure 5: Occurrence of the use cases of the electric truck projects in Elektro-Mobil.

optimised charging (5 projects: eHaul, UniSwapHD, ELMAR, NEFTON, SPIRIT-E). V2G primary balancing power and V2G redispatch are only considered in SPIRIT-E. It is striking that the use cases emergency power supply and power box are not analysed in any of the electric truck projects in Elektro-Mobil.

Looking at the survey results, questions remain that should be addressed in future studies. For example, it could be investigated why certain use cases are considered more and others less frequently. One possible question that could be considered is whether the more frequently represented use cases are the economically most interesting ones.

Looking at the aggregated use cases as shown in Figure 6, it can be seen that the truck projects in the Elektro-Mobil programme focus on the V2G and V2B use cases – these are considered 14 times each (38% of all use cases considered). The two V2H use cases are considered 9 times (24%). The V2H and V2B use cases can already be implemented for passenger cars in terms of technology and regulation, but there are still various challenges for the implementation of the V2G use cases.[132] What is already feasible for passenger cars (V2H and V2B) appears to be less interesting for the research projects working on electric trucks. In fact, the truck projects are particularly interested in what is not yet being implemented on the market for passenger cars – mainly V2G. Further studies could investigate the reasons for this. One possible question would be whether the findings from the passenger car sector are easily transferable to trucks, which is why there are such parallels in the research work.

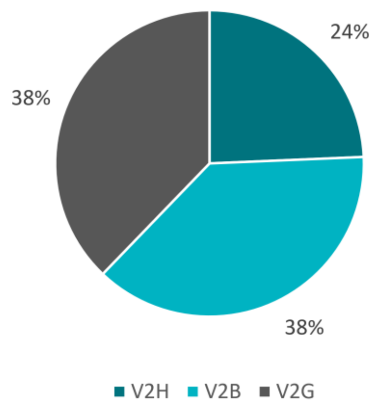

Figure 6: Aggregated use cases of the electric truck projects of Elektro-Mobil.

Context: Activities at EU level

In contrast to the electric truck projects in Elektro-Mobil, which cover the entire range of use cases from V2H to V2B and V2G in their research, the research projects at EU level only look at the use cases V2H tariff-optimised charging and V2B fleet management. Future studies could examine why the use case scope of the EU projects is smaller than that of the German projects and investigate whether the reason for this are different convictions regarding the economic viability of the use cases.

From 2017 to 2022, the INTERREG project "electric Green Last Mile" (eGLM) conducted cross-border research between Germany and the Netherlands on the requirements of various logistics transport companies with four EHDVs (40 and 44 t gross vehicle weight) on short journeys (max. 150 km). At night, the vehicles were charged with 50 kW at favourable electricity prices, and with 350 kW on the road.[133]

In 2022, the NextETRUCK project was launched, which is funded as part of the Horizon Europe programme and deals with efficient and affordable zero-emission logistics through the use of next-generation electric trucks. The focus is on regional medium goods transport (range up to 200 km). Eight countries are involved in the project with pilot sites in Istanbul (Ford, vehicle class N3), Utrecht (Tevva, vehicle class N3) and Barcelona (Irizar, vehicle class N3). At the Utrecht site in particular, fleet management tools will be used for load and charging management and the vehicles will be charged dynamically at favourable electricity prices. At the Istanbul site, the total cost of ownership (TCO) is also to be reduced by utilising variable energy costs, among other things.[134,135]

In the Netherlands, the "Living Lab Heavy Duty Laadpleinen" has been in place since 2022, within which test sites for EHDV charging infrastructure are set up at six locations in order to gather experience. In addition to spatial planning issues, integration into the energy infrastructure is also being investigated.[136]

3.2.2 Buses (M2-M3)

Activities at national level in Elektro-Mobil

The openness with regard to charging technology continues in the Elektro-Mobil projects that deal with electric buses. Although none of those 6 projects are working on a battery swapping system, 3 projects are researching megawatt charging and 1 project each is working on induction and overhead line charging, respectively (see Figure 7).

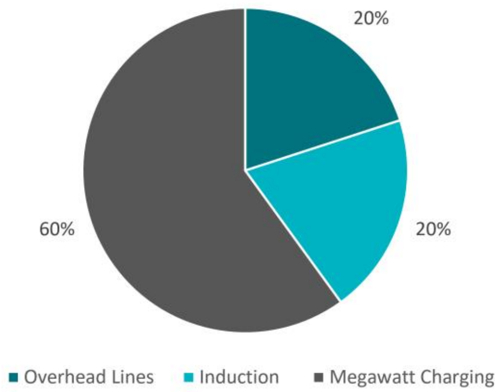

Figure 7: Charging technologies researched by electric bus projects in Elektro-Mobil.

Of the 6 bus projects, 4 (AMELIE 2, IDEAL, MEGA-LADEN and SPIRIT-E) are also conducting research into electric trucks and have already been presented in Chapter 3.2.1. ELINA and KoLa are exclusively researching electric buses and are briefly described in this chapter.

One focus of the research is on the use case of depot charging, which is at the centre of the electrification of bus fleets in public transport in particular. The KoLa project focuses on the charging and load management of bus depots in urban areas and is developing a controllable charging infrastructure for market-orientated and grid-friendly operation in the depot.[137] The charging processes are controlled unidirectionally and optimised bidirectionally, taking into account grid utilisation and electricity market prices. The ELINA project demonstrates how buses in public transport operations can be charged via induction coils embedded in the road while travelling.[138]

Figure 8 provides a tabular overview of the electric bus projects of Elektro-Mobil with regard to the considered vehicle classes, charging types, charging technologies, charging scenarios, research types, and use cases. If these projects are analysed in terms of "charging technologies", "charging scenarios" and "charging types" (see Chapter 2 for all aspects), the following picture emerges. In each case, 5 projects are researching non-public and public

Project	Charging type		Charging technology			Connec-tion type		Vehicle class		Charging scenario		Type of research			Use Cases												
	Controlled unidirectional	Bidirectional	Battery swapping	Megawatt charging / CCS2	Electric Road System	Conductive	Inductive	M2	M3	Non-public	Public	Study	Simulation	Development / Demonstration	V2H Self-consumption increase	V2H Tariff-optimised charging	V2B Peak shaving	V2B Fleet management	V2G Time-based arbitrage (intraday)	V2G Time-based arbitrage (day-ahead)	V2G Primary control power	V2G Local grid service	V2G Redispatch	V2G Reactive power provision	V2G Genuine green electricity	Emergency power supply	Powerbox
AMELIE 2	x				x	x			x		x		x	x													
ELINA	x				x		x		x	x	x		x	x													
IDEAL	x			x		x			x	x	x	x	x	x								x		x			
KoLa	x	x				x			x	x		x	x	x				x		x		x					
MEGA-LADEN	x			x		x		x	x	x	x			x													
SPIRIT-E	x	x		x		x			x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x		

Figure 8: Overview of the e-bus projects in Elektro-Mobil in terms of charging technology, type of connection, vehicle class under consideration, charging scenario, type of research and use cases in terms of grid integration.

charging scenarios. AMELIE 2 focusses exclusively on public charging and KoLa only on non-public charging; all other projects look at charging technologies for both charging scenarios.

All 6 Elektro-Mobil bus projects are researching unidirectionally controlled charging and 3 of these are also researching bidirectional charging (IDEAL, KoLa and SPIRIT-E). The projects were asked which use cases (analogous to the definitions of the use cases formulated in the BDL final report) they consider in their respective projects; the results can be found in Figure 9. The 3 bus projects dealing with bidirectional charging all consider the V2G local grid service use case. KoLa and SPIRIT-E are also looking at V2B fleet management and V2G time-based arbitrage (day-ahead). SPIRIT-E is also the only electric bus project to work on the use cases V2H self-consumption increase, V2H tariff-optimised charging, V2B peak shaving, V2G time-based arbitrage (intraday), V2G primary control power, V2G redispatch and V2G genuine green electricity.

If we look at the use cases in aggregate, we see that the electric bus projects – just like the electric truck projects – focus on the V2G use cases, even if the result is less meaningful due to the lower absolute number of use cases analysed. It is worth noting that – just like the truck projects – the two use cases emergency power supply and power box are also not researched in the electric bus projects.

Context: Activities at EU and international level

With a focus on V2G local grid services and V2G time-based arbitrage (day-ahead), the electric bus projects in Elektro-Mobil go beyond the scope of the European project ASSURED. Funded under the Horizon Europe programme from 2017 to 2021, ASSURED has shown how electric bus fleets can be implemented in European cities. In the cities of Bayonne and Biarritz (France), an intelligent charging strategy was developed for a fleet of 18 Irizar buses, in which the charging power was adapted to the power available in the grid. This enabled costs to be saved for the fleet operator through peak shaving.[139]

As stated in the previous paragraph, the use case emergency power supply is not considered in the electric bus projects of Elektro-Mobil. Chapter 3.1.2, on the other hand, mentioned that in North America the potential for the grid integration of school buses – in particular for emergency power supply – is considered to be great. In addition to initial practical examples (see Chapter 3.1.2), there are research projects on this topic. First Student is a leading provider of school transport solutions in North America, specialising in the electrification of school bus fleets. For example, Quebec (Canada) already

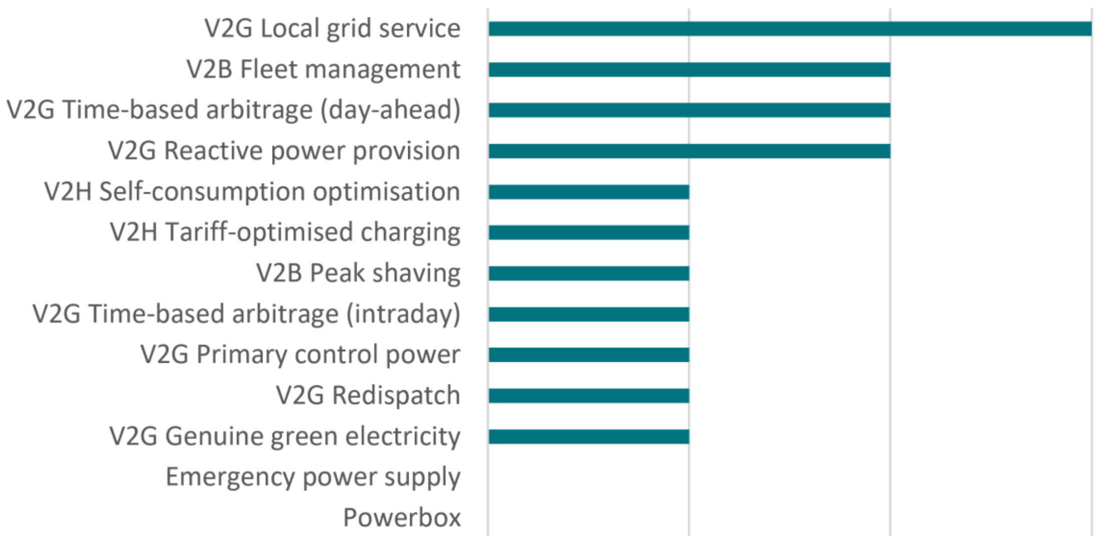

Figure 9: Frequency of the use cases of the electric bus projects in Elektro-Mobil.

has a fleet of 200 electric school buses, and First Student estimates that additional energy storage capacity of more than 7.4 GWh could be available if all of First Student's 46,000 buses were capable of V2G. This would be enough to power more than 33,000 average American homes for a week.[140,141] According to a study by the Frontier Group and the U.S. PIRG Education Fund from spring 2022, V2G technology is still in its infancy. Nevertheless, it illustrates that bidirectional electric bus fleets can reduce costs for fleet operators through peak shaving and arbitrage trading. If every school bus in the USA were to be electric and bidirectionally chargeable, this fleet would represent a 60 GWh storage facility that could also be used as emergency power supply, among other things.[118] Further studies could examine why so little attention is paid to emergency power supply from electric buses in the German research landscape. One possible question is what effect grid stability has in Germany compared to the USA.

3.3 Outlook

The previous chapters show that the integration of EHDVs into the grid will take place in stages. The first heavy commercial vehicles are being charged in a controlled manner at the depot (see Chapter 3.1). The research projects of the Elektro-Mobil funding programme are testing unidirectionally controlled and bidirectional charging of heavy commercial vehicles with various charging systems and use cases such as tariff-optimised charging, peak load capping and the provision of primary control power, among others (see Chapter 3.2). Recently, the programme has also focused on the aspect of asset sharing, e.g. for the shared use of non-public depot charging infrastructure, whereby controlled and bidirectional charging can also be implemented.

To date, there has been little or no activity towards unidirectionally controlled and bidirectional charging of high weight classes on public charging infrastructure on long-distance transport routes. Due to the high deadline pressure in the transport sector and the given charging and idle time windows, it is questionable whether these technologies can be used in this context during the working day. However, it is possible to apply these technologies during overnight charging stops as long as the vehicle is ready for use in the morning. This situation could change in a few years when batteries with higher energy densities are on the market and the range of EHDVs is no longer the limiting factor. For example, if a truck has a range of 1000 km and still has around 600 km left after a 4.5-hour shift, the driver will have to take a mandatory break, but will not necessarily have to recharge the vehicle. Depending on the route, the vehicle could even feed electricity back into the grid. Potential innovations that could bring about changes in operational management in the transport sector, such as autonomous driving, could have additional effects on the grid integration of heavy commercial EHDVs.

At the expert exchange "Smart and bidirectional charging of commercial vehicles – R&D projects and practical applications", which the accompanying research conducted virtually on 21 June 2023, the participants answered a Mentimeter survey. The answers reflect where the network integration of heavy goods transport is heading: the participants saw bidirectional charging for commercial vehicles mainly in special vehicles (23), in public transport (21), in the last mile (20) and on medium-haul routes (19), and only then in heavy long-haul transport (8). At this event, it was discussed that the challenges for V2X using EHDVs are that the provision of electricity at public charging infrastructure cannot be planned, the public charging infrastructure must also be capable of bidirectional charging, the vehicle must drive during the day and quickly reach its required range when charging.[142]

In a joint study, Daimler Truck and the transmission system operator TenneT TSO have investigated how the flexibility potential of charging electric trucks and buses can be utilised in the future.[143] Compared to the car sector, larger amounts of energy can be converted thanks to larger battery capacities. The flexibility of truck and bus batteries can be offered to transmission system operators to provide primary or secondary control power, as the batteries are able to react almost instantly to frequency deviations. The "line haul", "retail truck" and "bus depots" use cases described in the study in particular play a pioneering role in the morning hours; these use cases assume the use of both public and non-public charging infrastructure. In 2040, over 4000 MW of positive and negative flexibility potential could be made available between 4:00 PM and 04:00 AM.[143] The transmission system operators TenneT, Terna, Swissgrid, TransnetBW and APG have developed a so-called crowd-balancing platform called "Equigy", which has already been used in the Elektro-Mobil project BDL and will soon be used in the project SPIRIT-E as well to facilitate the grid integration of decentralised energy. Currently, the platform only executes unidirectionally controlled flexibilities but will also take bidirectional flexibilities into account in the future.

4 RECOMMENDATIONS FOR ACTION

From a vehicle technology perspective, the transition from combustion engine to purely battery-electric drive is feasible in the commercial vehicle sector. Models in vehicle classes N1-N3 and M2-M3 are either available on the market or at a very advanced stage of development. Based on the findings of the previous chapters, the accompanying research formulates three recommendations for action in order to support the market ramp-up of EHDVs and the necessary charging infrastructure. These recommendations address all relevant interest groups, including political policymakers at national and international level, local authorities, truck manufacturers, manufacturers and operators of charging infrastructure as well as stakeholders from the energy sector. All three recommendations are aimed at strengthening the market position of Germany and Europe in the area of grid integration of EHDVs in the long term.

4.1 Common language and transsectoral terminology

As discussed in Chapter 2 of this impulse paper, there are a number of ambiguities and inaccurate definitions of various terms. These include not only terms such as "grid-friendly" and „grid-supporting" (see Chapter 2.1.4). For example, the activities of the eHaul project, in which a battery swapping system including swapping station are developed, were subsumed under the terms V2H and V2B (see Figure 4), although strictly speaking, this is no longer backfeeding by a vehicle, as the batteries are removed from the vehicle and stored in the swapping station before they can interact with the power grid.

A certain blurring of terms is symptomatic of the merging of two sectors, from which an ecosystem is newly formed and organised. Clarifying terms at an early stage simplifies communication between the players and strengthens the common discourse. It may only take time for a "common jargon" to emerge, but it can be suggested that actors always put definitions first in publications. Using a common language, common priorities can be formulated more clearly and strategies can be pursued more effectively. After all, the common goal is clear: commercial vehicle transport should be decarbonised as quickly as possible in line with the climate protection targets. Truck manufacturers, transport companies, grid operators and other stakeholders must now define and take the next steps together through transsectoral communication and interdisciplinary cooperation.

All stakeholders should define terms before using them. Where possible, existing definitions should be used so that the existing discourse on the grid integration of commercial vehicles can be continued on a common knowledge basis. A common language also makes it easier for truck manufacturers, grid operators, transport companies and other stakeholders to formulate common priorities.

4.2 Closing knowledge gaps through targeted research

Chapter 3.2 clearly shows the knowledge gaps that still exist in the area of grid integration of EHDVs. In the Elektro-Mobil funding programme, certain use cases (of the V2G group) are considered more frequently, while other use cases (e.g. emergency power supply) are not being researched in any of the projects. It should also be emphasised that less research has been carried out on V2H and V2B in the electric truck projects of Elektro-Mobil than on V2G. This is interesting, as V2H and V2B can already be implemented in electric passenger cars in practice. One hypothesis to be tested is whether the findings from the passenger car sector are easily transferable to electric trucks, which is why less research work is needed on V2H and V2B for these vehicles. The accompanying research took a first step towards obtaining information on this topic in September 2023. Together with heavy-duty vehicle experts from the Elektro-Mobil programme, it was discussed whether the communication channels used to control charging processes for passenger cars (see the accompanying research white paper[19]) can be used to control charging processes for trucks. As a result, the experts stated that for EHDVs a separate communication map must be developed for each charging technology (see Chapter 2.3). It was also pointed out that a battery swapping system could possibly reduce the complexity of such a map, as there is no direct communication between the vehicle and the power grid since the battery swapping station acts as an interface.

Further studies could look at the economic efficiency of the use cases across all charging technologies and charging scenarios. However, the focus of the electric truck projects in Elektro-Mobil on V2G is also exciting for another reason. It is important to analyse whether the flow of information is also conceivable the other way round, i.e. whether the findings of the truck projects on V2G are also transferable to the passenger car sector.

In addition, further research activities should look at why certain use cases are focussed on in other countries and which framework conditions favor this focus. This could help to better understand these markets and, if necessary, be able to serve them. This paper has already taken a look at European and global activities in the field of grid integration of EHDVs – for example, the emergency power supply, which is intensively considered in the USA for electric buses, is not considered in Elektro-Mobil projects. The aim should be a global comparison of countries that are already at an advanced stage in the grid integration of EHDVs in order to analyse whether the findings are transferable to Germany. There is a great need to exchange best practices.

Researchers from funding projects, industry and research should close knowledge gaps regarding the transferability of findings from the passenger car sector to the commercial vehicle sector (and vice versa, where possible). A well-founded global comparison of pioneering projects in the field of grid integration of EHDVs would also be helpful.

4.3 Sharing knowledge and cooperation across Europe

The second recommendation for action leads directly to the third, as knowledge gaps can be closed more quickly and efficiently in an environment of lively communication and cooperation.

Due to its geographical location in Europe, Germany is a transit country; in 2021 alone, the proportion of foreign trucks on German roads was 42%. These vehicles will also undergo the transition to battery-electric drives in the coming years (decades). There are not only national, but also European climate targets that we want to help achieve through the electrification of heavy goods vehicle transport. There are also both national and European funding activities in the EU that can benefit even more from each other. The knowledge that we already have in the EU on the subject of grid integration and EHDVs is very decentralised. The question arises as to how this knowledge can be better exchanged at various levels – for example, how can a distribution system operator from the Elektro-Mobil programme share its experience with the more than 800 other German distribution system operators (nationally and in its own sector); how does this information flow via E.DSO (Europe's Distribution System Operators) to other European distribution system operators (European and in their own sector); how does the knowledge from a German funding programme flow into a Dutch funding programme and vice versa (trans-national); how does information from the German research landscape flow into European research projects (national and EU); etc.?

A first helpful step would be if the funded projects of national research programmes were obliged to publish all public project results not only in the respective national language, but also in English.

A central coordinating body that promotes controlled and bidirectional charging throughout Europe could take on the following tasks: Collecting all national research activities in this area in an overview, ensuring English translations from the national research projects, maintaining contacts and the European network as well as orchestrating further activities such as centralised exchange formats, conferences, or working groups.

European communication and cooperation must be facilitated and optimised. Research results must be made available internationally. A coordinating body at the European level can support this process and promote the dissemination of research results.

5 ATTACHMENTS

5.1 Appendix 1 to Chapter 3.1.1: Table with market overview of electric truck models

The following list is not exhaustive, but covers a large part of the available market offer.

Manufacturer	Model	Payload / t	Battery capacity / kWh	Charging power / kW (DC)	Range / km	Available from
BYD	ETH8	11,2	255	120	200	n. b.
DAF	CF Electric	28	315	250	220	2021
DAF	LF Electric	11,7	282	150	280	2021
DAF	XD Electric	28	525	325	500	2023
DAF	XF Electric	n. b.	525	325	500	2023
Daimler Truck	eActros 400	16,6	448	160	400	2021
Daimler Truck	eActros 600	n. b.	600	1000	500	2024
Daimler Truck	eEconic	17,7	336	160	150	2022
E-Force	EF18	18	450	150	500	2019
Irizar	he truck	13	300	100	250	2019
Iveco	Heavy Duty BEV	23,9	738	350	530	2023
MAN	eTGM	10,9	185	150	190	2019
Renault Trucks	E-Tech C	44 t zGg	540	250	n. b.	2023
Renault Trucks	E-Tech D	16 t zGg	565	150	560	2020
Renault Trucks	E-Tech D Wide	26 t zGg	375	150	315	2020
Renault Trucks	E-Tech T	44 t zGg	540	250	n. b.	2023
Scania	Electric Truck	40 t gt	624	375	320	2021
Scania	Electric Truck	64 t zGg	624	375	250	2021
Tesla	Semi	32,6	1000	1000	805	2022
Volvo Trucks	FE Electric	27 t zGg	375	150	300	2019
Volvo Trucks	FH Electric	23	540	250	300	2022
Volvo Trucks	FL Electric	16.7 t gt	540	150	450	2019
Volvo Trucks	FM Electric	23	540	250	300	2022

Different versions and axle configurations are available for most models, which is why the values for payload, charging power and range are only maximum values for the specific model. In some cases, the battery capacities are maximum values that are not fully approved for use. In some cases, the payload could not be determined; in these cases, the gross vehicle weight rating (GVWR) is stated. In some cases, the maximum range without intermediate charging was not specified. No distinction was made between tractor trucks and panel vans.

5.2 Appendix 2 to Chapter 3.1.1: Table with market overview of charging infrastructure

Provider	Name	Charging power (max.)	AC/DC	V2H	V2G
openWB	Pro	11 kW, 22 kW	AC	Yes	Yes
Wallbox Chargers	Quasar 2	12.8 kW	DC	Yes	Yes
Smartfox	Pro Charger 2	22 kW	n.b.	Yes	Yes
E3/DC	Edison V2H	n. b.	DC	Yes	Yes
E3/DC	S10 M	n. b.	n.b.	Yes	Yes
SolarEdge	n. b.	24 kW	DC	Yes	Yes
Evtec	sospeso&charge	10 kW	DC	Yes	-
dcbel	r16	15.2 kW	AC	Yes	Yes
Kostal	BDL Wallbox	11 kW	DC	Yes	Yes
Eaton	Green Motion DC 22	22 kW	DC	Yes	Yes
sun2wheel	two-way digital CHAdeMO	10 kW	DC	Yes	Yes
sun2wheel	two-way-10	10 kW	DC	Yes	Yes
sun2wheel	two-way digital CCS	10 kW	DC	Yes	Yes
Silla	Duke 44	22 kW	DC	Yes	Yes
Ambibox	ambiCHARGE	22 kW	DC	-	-
Ambibox	ambiCHARGE	11 kW	DC	Yes	Yes
Mobilise	Powerbox	22 kW	DC	Yes	Yes
Enteligent	Hybrid	25 kW	DC	Yes	-
Enphase	Bidirectional wallbox	-	n.b.	Yes	Yes
Ford	Charge Station Pro	19 kW	DC	Yes	-
VW	bidirectional ID. Charger	-	DC	Yes	Yes
Sono	Wallbox	11 kW	AC	Yes	Yes
Wallbox Chargers	Quasar 1 (chademo)	7.4 kW	DC	Yes	Yes
Sigenergy Technology	SigenStor + EV DC Charging Module	25 kW	DC	Yes	Yes
Ionix	AVA	25 kW	DC	Yes	-
Eaton	Green Motion DC 44/66	44 kW, 66 kW	DC	-	Yes
Alpitronic	HYC50	50 kW	DC	-	Yes

5.3 Appendix 3 to Chapter 3.2: Project boxes

AMELIE 2	Funding call: III	Duration: 11.2020-10.2023
Long name Billing systems and methods for electrically powered trucks and their interoperable infrastructures in the European context		
Brief description The "AMELIE 2" research project is developing a technically, legally and organisationally feasible model for the operation of overhead line systems in the road network. The focus is on developing a model that finds solutions for billing and regulatory issues relating to an electric road system. In addition, obstacles identified in the previous project will be resolved. This includes the development of a practicable legal framework. At the same time, the model offers a scenario for how the electric road system can be integrated into the existing structures of the energy industry and motorways.		
Grid integration The increased regulatory requirements due to mobile energy consumers with grid supply and on-board energy storage in road traffic are analysed with regard to grid load (active and reactive load).		
Keywords Unidirectionally controlled, ERS: overhead line, N2, N3, M3, public charging scenario: dynamic charging on the overhead line, simulation, demonstration, prototypes		

E|MPOWER	Funding call: V	Duration: 07.2022-06.2025
Long name Automated production processes for electric road systems for the electrification of heavy goods transport		
Brief description The E|MPOWER project focuses on inductive charging technologies for heavy goods vehicles to charge them while travelling. As part of the research project, production technologies suitable for large-scale production as well as innovative and automated manufacturing and construction processes are being developed to create the basis for mobile charging while driving. From the production of the coils to the installation of these in the roads, scalable standards are being developed at both process and technological level.		
Grid integration Similar to driving on the overhead line, dynamic charging during the journey distributes the called-up charging power drawn over the entire route and the journey time travelled on the electrified road. There is no local or temporal concentration of the drawn charging power, which results in a significantly lower impact on the power grid compared to stationary charging.		
Keywords Unidirectionally controlled, public charging scenario: dynamic charging via induction, N1-N3, demonstration		

eHaul	Funding call: III	Duration: 10.2020-09.2023

Long name

Electrification of long haul heavy-duty commercial vehicles with automated battery swapping station

Brief description

Development of a fully automatic battery changing system for electric trucks. The "eHaul" project allows electric trucks to be fully charged within minutes. To that end, the project is developing a fully automated battery swapping system for electric trucks with a gross vehicle weight of up to 42 t. By automatically swapping the batteries at specially designed, accessible battery swapping stations, even heavy electric trucks can cover long distances without unnecessary delays. The batteries are swapped by robots inside the station, which are equipped with optical sensors. This means that the batteries are replaced without any intervention from the drivers or other personnel and the journey only has to be interrupted briefly. The technology is being tested under real-world conditions with a logistics fleet on a route between Berlin and Dresden.

Grid integration

The charging infrastructure is designed to be bidirectional, so that the stored swapping batteries can be used as buffer storage to charge other swapping batteries in addition to the power of the grid connection.

Keywords

Unidirectionally controlled, bidirectional, BSS, N3, non-public charging scenario: own and third-party company premises, public charging scenario: charging hub on motorways, simulation, demonstration, V2H tariff-optimised charging/discharging, V2B peak shaving, V2B fleet management

ELINA	Funding call: V	Duration: 07.2022-06.2025

Long name

Use of dynamic charging infrastructure in public transport

Brief description

The ELINA project is developing an automated planning process that promotes the development of inductive charging systems for local public transport. For example, it supports the efficient planning of route electrification for electric bus routes, which facilitates the introduction and operation of inductive charging technologies. From May 2023, a demonstration system with a suitable electric bus will be operated in the town of Balingen in Baden-Württemberg. The measured values and experience gained from this public transport operation will be incorporated into the development of the planning process and further investigations.

Grid integration

As part of the project, energy system repercussions will be modelled and emission savings during the operating phase of inductive charging will be investigated in comparison to alternative charging technologies. In addition, a qualitative presentation of technical requirements and necessary adjustments to grid operating parameters for the integration of inductive charging points into the distribution grid will be carried out.

Keywords

ERS: Induction, M3, non-public charging scenario: own and third-party company premises, simulation, development, demonstration

ELMAR	Funding call: V	Duration: 08.2022-07.2025

Long name

Integration and demonstration of the use of electric heavy-duty transport machines in the raw materials industry

Brief description

To date, there are no concepts for the electrification of vehicles such as trucks or construction machinery in the domestic raw materials extraction industry, even though this sector is one of the most energy-intensive industries in Germany. The ELMAR project is therefore developing the first meaningful pilot concepts to research and demonstrate the use of electric means of transport in representative raw materials extraction companies, taking into account the local energy infrastructure. Based on the data available and the resulting findings, strategies are to be developed that will enable the entire industry to move into electromobility.

Grid integration

The transport of raw materials and the charging cycles are planned using models via the cloud applications for optimised electrical operation. Coordinated charging of the transport vehicles and the possible use of a buffer battery avoids peak loads and demonstrates a reduction in the increase in the required grid connection power. With the flexibilisation of the local electricity system and the data obtained, the integration of the company's own photovoltaic systems is being tested in a simulation.

Keywords

Unidirectionally controlled, bidirectional, N3, non-public charging scenario: own company premises, demonstration, V2H self-consumption increase, V2H tariff-optimised charging/discharging, V2B peak shaving, V2B fleet management, V2G genuine green electricity

enERSyn	Funding call: V	Duration: 08.2022-07.2025

Long name

Investigation of technical, economic, ecological and energy-related synergies of Electric Road Systems (ERS) with other truck drive train technologies

Brief description

The enERSyn project is researching the dependencies and synergies of various energy supply and charging solutions in future electrified road freight transport. The project is focussing in particular on electric road systems, which allow trucks to be charged while driving, for example via overhead lines. The effects of the various combinations of solutions on the power grid, climate and economic efficiency are also being analysed and system costs calculated. The results will be published in a final report and various other publications.

Grid integration

The enERSyn project looks at the interface between the energy and transport sectors. This is achieved by quantitatively analysing the interactions of different charging technologies with the energy system, with a particular focus on ERS concepts. The potential benefits of market-driven and possibly bidirectional charging are also quantified.

Keywords

Unidirectionally controlled, bidirectional, ERS: overhead line, conductor rail and induction, megawatt charging, BSS, N2 and N3, non-public charging scenario: own and third-party depot, public charging scenario: transfer point, charging hub in commercial areas and on motorways, study, simulation, V2H self-consumption increase, V2B peak shaving

eVTrailer2	Funding call: V	Duration: 08.2022-07.2025

Long name

Electric drive co-operation and energy system for heavy commercial vehicles

Brief description

In the eVTrailer2 project, the project partners are focusing on the "articulated truck" commercial vehicle type and are developing options for electrifying the semi-trailer, a previously non-motorised component of the vehicle. The project partners want to utilise the space typically available here to further develop the articulated truck into an intelligent, safe and emission-reduced vehicle system for road freight transport through the combination of integrated photovoltaic modules and electric drive. By electrifying the trailer and generating its own PV power, the range of the tractor unit is extended and the traction energy becomes even "greener".

Grid integration

The project is developing a suitable system architecture for vehicle-side HV energy storage with a high-current-capable HV box with charge controller for bidirectional HPC (High Power Charging) for integration into fast charging points.

Keywords

Unidirectionally controlled, bidirectional, megawatt charging, ERS: overhead line and induction, N3, O4 (semi-trailers), non-public charging scenario: own and third-party company premises, public charging scenario: charging hub on motorways, demonstration, V2B peak shaving, V2B fleet management, V2G local grid service

HV-MELA-BAT	Funding call: V	Duration: 08.2022-07.2025

Long name

High-voltage megawatt charging system with buffer storage for battery-powered heavy goods and passenger transport

Brief description

The HV-MELA-BAT project is developing, building and testing a one-megawatt charging system for high-performance charging in battery-powered heavy goods and passenger transport. The focus is on the development of innovative components that enable safe and efficient charging in the high-voltage and megawatt range. The power density and power-to-weight ratio of the power electronics developed in the project should also improve the cost-effectiveness of future megawatt charging systems of over one megawatt. The project is also pursuing a modular approach that also allows lower charging rates and thus ensures compatibility with the existing battery-electric car sector.

Grid integration

The project will utilise a battery storage system that can feed back into the electricity grid bidirectionally. Load peaks can be smoothed out using the buffer storage system. The bidirectional converter for the buffer storage and all other necessary converter stages are optimised in terms of power density so that a compact design of the overall system is possible. In the event of problems, new circuit variants or components may have to be found that can be designed to save space.

Keywords

Unidirectionally controlled, bidirectional, megawatt charging, N3, non-public charging scenario: own company premises, demonstration, V2B peak shaving

IDEAL	Funding call: IV	Duration: 06.2021-05.2024

Long name

Innovative DC technology for the sustainable integration of modern charging infrastructure for electromobility

Brief description

The IDEAL project is researching innovative, DC-based charging solutions for electromobility in order to enable reliable fast-charging infrastructures at reasonable cost and effort. The aim is to develop charging stations that can be equipped with compact and cost-effective power electronics without jeopardising the stability of the power grid. The existing infrastructure can be optimally utilised so that new installations of electrical equipment can be reduced. Technologies are being developed for high-performance charging and urban charging systems in the medium kilowatt range.

Grid integration

The project is developing fast and high-performance charging systems for commercial transport and heavy goods transport in the megawatt range. For the DC bus supply, both bidirectional and unidirectional solutions are to be considered, which may offer additional cost optimisation potential. In addition to the charging infrastructure, a connector is being developed on the vehicle side that can transmit charging power in the megawatt range with optimised cooling.

Keywords

Unidirectionally controlled, bidirectional, megawatt charging, N3, M3, non-public charging scenario: own company premises, public charging scenario: transshipment points and charging hubs in commercial area, simulation, study, demonstration, V2G local grid service, V2G reactive power provision

KoLa	Funding call: V	Duration: 07.2022-06.2025

Long name

Coordination function of the distribution grid and load management for electrified passenger transport

Brief description

The aim of the project is to develop and test a coordination platform for the electricity distribution grid. In order to optimise the charging processes of Hamburger Hochbahn's electric buses, a load management system is also being developed and implemented that takes into account the requirements of bus operation, electricity grid utilisation in the distribution grid and current electricity market data (prices). The aim is to intelligently control the charging times of the electric buses and expand the existing systems of Hamburger Hochbahn by integrating new systems and interfaces. In addition, a battery storage system is to be set up and utilised for the first time – consisting of 2nd-life batteries, subject to market availability.

Grid integration

The current state of the grid is taken into account by the first-time implementation of a so-called coordination function, which is being developed as part of the project. This coordination function forecasts the status of the grid. The optimisation system at load management level determines energy requirements, flex potential and an optimal charging schedule based on the operational specifications. An exchange takes place between the coordination function and the optimisation system via the charging schedules determined in this way. The coordination function evaluates the grid compatibility of the planned charging processes of all grid area participants and decides whether the plan can be implemented as it is or whether it needs to be adapted for the grid.

Keywords

Unidirectionally controlled, bidirectional, M3, non-public charging scenario: own company premises, study, simulation, demonstration, V2B fleet management, V2G time-based arbitrage (day-ahead), V2G local grid service

MEGA-LADEN	Funding call: III	Duration: 10.2020-09.2023
Long name Megawatt fast charging for electric commercial vehicles in logistics		
Brief description The aim of the "MEGA-LADEN" project is to develop and demonstrate a fully automated fast-charging system for electric trucks in the megawatt range. This allows large truck batteries to be charged easily during loading and unloading or during lawfully mandated break times. This is made possible by an automatic fast-charging interface with a charging capacity of more than one megawatt. The automatic charging process with high charging power means a major gain in convenience for users, increases the acceptance of e-mobility in the logistics sector and allows electric recharging even for people without specialised knowledge.		
Grid integration The project is developing an automatic fast-charging interface in the multi-megawatt range for electric commercial vehicles and optimising the system for the logistics application. To this end, a power-electronic charger including multi-point charging management for different contact systems and sequential power distribution is being developed for the logistics hub application. The fast-charging capability and the economically optimised applicability of fast charging for electric trucks in logistics applications are to be demonstrated.		
Keywords Unidirectionally controlled, megawatt charging, N1-N3, M2-M3, non-public charging scenario: own and third-party company premises, public charging scenario: transshipment points, charging hubs in industrial estates and on motorways, demonstration		

NEFTON	Funding call: IV	Duration: 06.2021-05.2025

Long name

Commercial vehicle electrification for transport sector-optimised grid connection

Brief description

The NEFTON project is developing a prototypical overall concept for electric commercial vehicles and a fast-charging infrastructure with a capacity of over one megawatt in order to lay the foundations for the decarbonisation of road freight transport in Germany. As part of the project, the findings from the development of these systems and from further research will be recorded in an "MCS user manual" with recommendations for action for vehicle manufacturers and charging infrastructure operators, for example. The concept will also be tested as a prototype using a developed truck and a charging station.

Grid integration

In the project, (fast) charging infrastructure concepts are tested for feasibility and cost-effectiveness. In coordination with the vehicle and user requirements, the unidirectional and bidirectional power electronics of the charging infrastructure are designed, prototypically implemented and their effects on the energy supply analysed. Three energy paths are being implemented for the charging system by using highly efficient unidirectional and bidirectional power electronics modules and innovative wiring. On the one hand, the aim is to enable a combination of the 800 kW grid connection (energy path 1) and a buffer battery (energy path 2) in order to provide a charging capacity of over 1 MW. Furthermore, the bidirectional modules can be used to provide energy from the vehicle battery or buffer battery for grid service applications.

Keywords

Unidirectionally controlled, bidirectional, megawatt charging, N3, non-public charging scenario: own company premises, public charging scenario: charging hub in commercial areas and on motorways, simulation, demonstration, V2H self-consumption increase, V2H tariff-optimised charging/discharging, V2G time-based arbitrage (intraday and day-ahead)

SPIRIT-E	Funding call: VI	Duration: 08.2023-07.2026

Long name
Shared Private Charging Infrastructure and Reservation for Bidirectionally Integrated Truck Electrification (SPIRIT-E)

Brief description
The aim of SPIRIT-E is to demonstrate the successful, innovative and economical integration of electric commercial vehicle fleets into the energy system using the core innovations of reserving "shared depot" charging infrastructure, i.e. locations with secondary semi-public use of the charging infrastructure, which enables the use and billing of commercial vehicles from outside the transport sector.

Grid integration
Field tests are being carried out on bidirectional charging and the system integration of battery-electric commercial vehicles at logistics locations and a shared depot. Economic simulations of secondary, energy-related use cases of the commercial vehicles are carried out, in which third-party vehicles are also included in the calculations. The simulative study is based on real data including validation through field tests. In addition to the field tests, the digital infrastructure for the scalable use of these innovations is also being created.

Keywords
Unidirectionally controlled, bidirectional, megawatt charging, N3, M3, non-public charging scenario: own and third-party premises, public charging scenario: transfer points, simulation, demonstration, V2H self-consumption increase, V2H tariff-optimised charging/discharging, V2B peak shaving, V2B fleet management, V2G time-based arbitrage (intraday and day-ahead), V2G primary control power, V2G local grid service, V2G redispatch, V2G reactive power provision, V2G genuine green electricity

UniSwapHD	Funding call: V	Duration: 01.2023-12.2025

Long name
Unified Swappable Battery for Heavy Duty Commercial Vehicles

Brief description
The aim of the project is to provide explicit answers to questions relating to the standardisation of swappable traction batteries.

Grid integration
The automatic battery swap stations make it possible to offer grid services in variable power ranges through bidirectional charging. UniSwapHD thus supports the economic utilisation of the approaches that are being prototypically implemented in the eHaul project.

Keywords
Unidirectionally controlled, bidirectional, BSS, N3, non-public charging scenario: own and third-party company premises, public charging scenario: charging hub on motorways, simulation, demonstration, V2H tariff-optimised charging/discharging, V2B peak shaving, V2B fleet management

References

[1] European Green Deal: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_de

[2] EU Transport in Figures, 3.2.7 GHG emissions from road transport: https://op.europa.eu/en/publication-detail/-/publication/f656ef8e-3e0e-11ed-92ed-01aa75ed71a1

[3] ACEA Report - Vehicles in Use Europe 2022: https://www.acea.auto/files/ACEA-report-vehicles-in-use-europe-2022.pdf

[4] Federal Climate Protection Act in the version dated 24 June 2021: https://www.bmuv.de/gesetz/bundes-klimaschutzgesetz

[5] The German government's 2030 climate protection programme: https://www.bmel.de/SharedDocs/Downloads/DE/_Landwirtschaft/Klimaschutz/Klimaschutzprogramm2030.pdf?__blob=publicationFile&v=3

[6] Impulse paper of the accompanying research on the transformation of the automotive industry: https://www.iit-berlin.de/publikation/transformation-der-automobilen-wertschoepfungsketten/

[7] Tol et al, 2022, Techno-economic uptake potential of zero-emission trucks in Europe: https://www.agora-verkehrswende.de/fileadmin/Veranstaltungen/2022/Elektrische-Lkw/TNO_2022_R11862_Techno-economic_uptake_potential_of_zero-emission_trucks_in_Europe.pdf

[8] Joint declaration of intent by European truck manufacturers on decarbonisation by 2040: https://www.acea.auto/publication/acea-pik-joint-statement-the-transition-to-zero-emission-road-freight-transport/

[9] Daimler Truck aims to sell more trucks with electric drive systems than with combustion engines in Europe by 2030: https://www.handelsblatt.com/technik/thespark/lastwagenhersteller-daimler-truck-will-2030-in-europa-mehr-lkw-mit-e-antrieb-verkaufen-als-mit-verbrennungsmotor/27632388.html

[10] Volvo Trucks wants around 50 per cent of new trucks sold worldwide to be electric by 2030: https://www.volvotrucks.de/de-de/news/press-releases/2023/mar/volvo-trucks-zeigt-elektromobilitaet-und-neue-digitale-services-auf-der-transport-logistic-2023.html

[11] Scania is aiming to only bring commercial vehicles with electric motors onto the market from 2040: https://www.eurotransport.de/artikel/traton-will-vorreiter-sein-scania-ab-2040-nur-noch-elektrisch-11213361.html

[12] Volvo aims to sell only all-electric trucks from 2040: https://www.volvotrucks.de/de-de/news/press-releases/2023/may/elektrische-lkw-nehmen-fahrt-auf-volvo-trucks-behaelt-seine-fuehrende-position.html?sc_cid=pnttemplate_email_%253c%2525%253dcontext.targetdata.cta%2525%253e

[13] Evaluation of the NOW GmbH clean room discussions: https://www.klimafreundliche-nutzfahrzeuge.de/marktentwicklung-klimafreundlicher-technologien-im-schweren-strassengueterverkehr/

[14] The development of electric trucks in (inter)national logistics in the Netherlands: https://elaad.nl/wp-content/uploads/2022/05/20Q3_Elaad_Outlook_E-trucks_internationale_logistiek.pdf

[15] K. Göckeler et al, 2023. Future transport market will be characterised by BEV commercial vehicles: https://www.oeko.de/fileadmin/oekodoc/StratES-Szenarien-Elektrifizierung-Strassengueterverkehr.pdf

[16] BGL calls for more truck parking spaces on motorways: https://www.bgl-ev.de/35-000-bis-40-000-lkw-stellplaetze-fehlen-an-deutschen-autobahnen/

[17] Final report of the electric mobile project BDL: https://www.ffe.de/wp-content/uploads/2023/03/BDL-Abschlussbericht.pdf

[18] Definition of grid integration: https://electrificationcoalition.org/wp-content/uploads/2022/06/Advancing-V2G-Technology-Adoption.pdf

[19] Whitepaper of the accompanying research Elektro-Mobil on the control of charging processes: https://consulting.tuv.com/aktuelles/trc-news/steuerung-ladevorgaenge-elektromobilitaet

[20] Statements by experts from the Elektro-Mobil funding programme at the programme's internal "heavy-duty breakfast" on 29.09.2023.

[21] Classification of grid integration: https://www.oeko.de/fileadmin/oekodoc/Gesamtbericht-Wirtschaftlichkeit-von-Elektromobilitaet.pdf

[22] Definition of grid-supporting and system-supporting: https://www.ffe.de/wp-content/uploads/2021/05/20210122_Was-ist-Netzdienlichkeit_num_LV.pdf

[23] Definition of market-serving: https://www.bdew.de/media/documents/Stn_20211004_Marktdesign2030.pdf

[24] Cars and trucks, as of 01.01.2023; https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Transport-Verkehr/Unternehmen-Infrastruktur-Fahrzeugbestand/Tabellen/fahrzeugbestand.html

[25] IPEK vehicle classes: https://www.ipek.kit.edu/11386.php

[26] VDV motor coach: https://www.mobi-wissen.de/Verkehr/Kraftomnibus#:~:text=A%20motor%20coach%20(Kom)%20is%20one,eight%20seats%C3%A4tzen%20next%20to%20the%20driver%20seat

[27] National control centre for charging infrastructure for commercial vehicles: https://nationale-leitstelle.de/nutzfahrzeuge/

[28] Handbook for the development of charging infrastructure in depots for electric heavy goods transport: https://www.agendalaadinfrastructuur.nl/ondersteuning+gemeenten/documenten+en+links/documenten+in+bibliotheek/handlerdownloadfiles.ashx?idnv=2403872

[29] Easy charging at motorway service areas: https://nationale-leitstelle.de/wp-content/uploads/2022/09/Leitstelle_LKW-Netzstudie.pdf

[30] Burges and Kippelt, 2022. Grid-Related Challenges of High-Power and Megawatt Charging Stations for Battery-Electric Long-Haul Trucks: https://te-cdn.ams3.digitaloceanspaces.com/files/2022_01_TE_grid_integration_long_haul_truck_charging_study_final.pdf

[31] Adolf et al, 2010. Shell Truck Study, Trends and prospects in road freight transport up to 2030: https://elib.dlr.de/64553/

[32] Hacker et al, 2022. Possible expansion steps for an overhead line infrastructure for road freight transport in Germany: https://www.ifeu.de/fileadmin/uploads/BOLD-Oberleitungsinfrastruktur-Deutschland.pdf

[33] Gnann et al. 2023, BOLD - Accompanying research for overhead catenary trucks in Germany. Final report: https://doi.org/10.24406/publica-2002

[34] https://www.railwaypro.com/wp/worldwide-rail-electrification-remains-at-high-volume/

[35] Jöhrens et al, 2020. Roadmap for the introduction of an overhead line truck system in Germany: https://www.ifeu.de/fileadmin/uploads/2020-08-05-Roadmap-OH-Lkw-web.pdf

[36] Sharpe and Basma, 2022. International Council on Clean Transportation: A meta-study of purchase costs for zero-emission trucks: https://theicct.org/wp-content/uploads/2022/02/purchase-cost-ze-trucks-feb22-1.pdf

[37] Hacker et al, 2020. StratON evaluation and introduction strategies for overhead line-bound heavy commercial vehicles, final report: https://www.oeko.de/fileadmin/oekodoc/StratON-O-Lkw-Endbericht.pdf

[38] MCS standard of the CharIN: https://www.charin.global/technology/mcs/

[39] Mercedes-Benz eActros LongHaul in pre-production: https://media.daimlertruck.com/marsMediaSite/de/instance/ko/Absichtserklaerung-unterzeichnet-DB-Schenker-uebernimmt-100-eActros-LongHaul-in-seinen-Fuhrpark.xhtml?oid=52194928

[40] MAN produced new e-trucks in 2024: https://press.mantruckandbus.com/corporate/de/man-beschleunigt-wandel-zu-nullemissionsantrieben/

[41] Production start of Tesla Semi: https://www.electrive.net/2022/10/07/produktionsstart-fuer-den-tesla-semi/

[42] Designwerk e-truck with a battery capacity of 1000 kWh: https://www.designwerk.com/post/presse/designwerk-bricht-megawattstunden-grenze/

[43] Weight of a battery with 1000 kWh: https://www.designwerk.com/elektro-lkw-high-cab/

[44] Daimler Truck eActros 600: https://www.daimlertruck.com/newsroom/pressemitteilung/mercedes-benz-eactros-longhaul-feiert-weltpremiere-als-eactros-600-im-oktober-produktionswerke-bereiten-serienfertigung-vor-52260702

[45] Overview of e-trucks from MAN: https://www.man.eu/de/de/lkw/elektro-lkw/uebersicht.html

[46] Volvo FL Electric: https://www.electrive.net/2023/06/20/batterie-update-fuer-volvo-fl-electric-und-fe-electric/

[47] Grid connection capacity of a small town with 50,000 inhabitants: https://www.energie.fraunhofer.de/de/presse-medien/aktuelle-presseinformationen/presseinformationen-2019/PI-190704-fraunhofer-ise-leistungselektronik-fuer-die-energiewende

[48] Interactive map of potential locations of public charging parks in Germany: https://hochleistungsladen-lkw.de/hola-en/interactive-location-map-for-charging-infrastructure.php

[49] T&E study 2021 electric truck fast-charging infrastructure: https://www.transportenvironment.org/wp-content/uploads/2021/07/202102_pathways_report_final.pdf

[50] RouteCharge project: https://www.digitale-technologien.de/DT/Redaktion/DE/Downloads/Publikation/IKT-EM/ikt3-pm-RouteCharge%202020.pdf?__blob=publicationFile&v=1

[51] Project eHaul: https://www.ehaul.eu/

[52] Nio is trialling the provision of ancillary services with stored swap batteries in Denmark: https://www.nio.com/de_DE/news/202402220004

[53] Battery-powered trucks in China in 2022: https://theicct.org/china-is-propelling-its-electric-truck-market-aug23/

[54] "Challenges and requirements of megawatt charging infrastructure for long-haul trucks", Bonjad Satvat, abstract presented at EVS36, June 2023.

[55] "Charging the electric truck fleet - Learnings from Dutch frontrunners in zero emission logistics", Harm Weken, abstract presented at EVS36, June 2023.

[56] "Solving the charging challenge for commercial electric fleets", Pamela Macdougall, abstract presented at EVS36, June 2023.

[57] "Real-world energy efficiency analysis and implications: medium-duty and heavy-duty EV deployments across the US", Yin Qiu and Cristina Dobbelaere, abstract presented at EVS36, June 2023.

[58] Market overview of current electric vans 2023: https://www.autoscout24.de/informieren/ratgeber/beste-autos/elektro-transporter/

[59] Market overview of current electric vans: https://www.adac.de/rund-ums-fahrzeug/elektromobilitaet/kaufen/e-transporter/

[60] Guide for the installation of charging systems for electric vehicles 2021: https://www.swiss-emobility.ch/de-wAssets/docs/merkblaetter/Externe-Merkblaetter/Ratgeber_fuer_die_Installation_von_Ladesystemen_fuer_eFahrzeuge_2021.pdf

[61] Ford F-150 Lightning: https://efahrer.chip.de/tests/ford-f-150-lightning-im-ersten-fahrtest-hart-eingepreister-dreitonnen-pick-up_107987

[62] Ford Electric Transit: https://efahrer.chip.de/news/ford-bringt-elektro-transit-reichweite-leistung-und-nutzlast-sind-spitze_109404

[63] VW ID. Buzz and ID. Cargo: https://www.elektroauto-news.net/news/vw-id-buzz-id-cargo-82-kwh-akku-150-kw-leistung

[64] Market overview of bidirectional wallboxes, as of October 2023: https://bidirektionale-wallboxen.de/marktuebersicht/

[65] The new Volkswagen ID. Buzz: https://www.wunschwagen.de/magazin/news-aus-der-branche/der-neue-volkswagen-id-buzz

[66] Tesla fast charging station: https://electrek.co/2023/07/26/tesla-confirms-supercharger-v4-350-kw-output/

[67] Ekoenergetyka fast charging station: https://ekoenergetyka.com.pl/products/sat-600-hpc/

[68] Tritium fast charging station: https://tritiumcharging.com/product/pk-350/

[69] Fig Fast charging station: https://new.abb.com/ev-charging/de/terra-360

[70] Elexon fastcharging station: https://elexon-charging.com/wp-content/uploads/2023/09/elexon_DB_DC-Ladestation_DE_0823_8seiter_digital.pdf

[71] Alpitronic fast charging station: https://www.alpitronic.it/de/hypercharger/hyc-400/

[72] Kempower fast charging station: https://mediabank.kempower.com/l/VBRk-xfMK6vg

[73] Federal Government's Charging Infrastructure Masterplan II: https://bmdv.bund.de/SharedDocs/DE/Anlage/G/masterplan-ladeinfrastruktur-2.pdf?__blob=publicationFile

[74] Demand for implementation of measure 62: https://www.baden-wuerttemberg.de/fileadmin/redaktion/dateien/PDF/SDA_BW/231207_SDA_Impulspapier.pdf

[75] Development of fast-charging parks by Milence: https://milence.com/news/milence-accelerates-europes-shift/

[76] Aral fast-charging corridor: https://www.aral.de/de/global/retail/presse/pressemeldungen/pm-2023-aral-eroeffnet-europas-ersten-ladekorridor-fuer-elektrische-lkw.html

[77] Swedish companies are planning a fast-charging network for electric trucks: https://www.electrive.net/2023/01/13/kooperation-plant-e-lkw-ladenetz-in-schweden/

[78] StreetScooter at DHL: https://dhl-freight-connections.com/de/nachhaltigkeit/schon-10-000-streetscooter-klimaschonend-unterwegs/

[79] Mercedes-Benz eVito at DP DHL: https://www.manager-magazin.de/fotostrecke/elektro-lieferwagen-mercedes-e-vito-vs-streetscooter-fotostrecke-155566.html

[80] Ford E-Transit at DP DHL: https://logistik-heute.de/news/elektromobilitaet-deutsche-post-dhl-bringt-2000-ford-elektrotransporter-auf-die-strasse-38591.html

[81] Iveco eDaily at DP DHL: https://www.iveco.com/germany/iveco-entdecken/Pressebereich/Presseinformation/2010/IvecoElectricDailybeiderDeutschePostDHL

[82] Volvo FL Electric at DP DHL: https://group.dhl.com/de/presse/pressemitteilungen/2023/deutsche-post-dhl-setzt-neue-elektro-lkw-flotte-in-berlin-ein.html

[83] Network integration at DP DHL: https://www.bundesnetzagentur.de/DE/Beschlusskammern/1_GZ/BK6-GZ/2022/BK6-22-300/Stellungnahmen/Deutsche Post DHL Group.pdf?__blob=publicationFile&v=1

[84] Fleet operations at DP DHL: https://www.now-gmbh.de/wp-content/uploads/2022/11/NFZ22_Flottenbetrieb-leichter-E-Nutzfahrzeuge_SalomonMeyer.pdf

[85] Overhead line trucks at DP DHL: https://www.elektroauto-news.net/news/dhl-elektro-lkw-oberleitung

[86] Press release: https://www.volvotrucks.at/de-at/news/press-releases/2023/jan/73-volvo-fm-fuer-die-oesterreichische-post-ag.html

[87] Use of e-trucks at Österreichische Post AG: https://www.electrive.net/2022/02/08/schwedischer-spediteur-falkenklev-elektrifiziert-depot-in-malmoe/

[88] Use of e-trucks at Falkenklev Logistik: https://theevreport.com/scania-to-supply-electric-trucks-to-falkenklev-logistik

[89] Use of e-trucks at Einride: https://www.electrive.net/2023/05/12/rewe-flottet-mithilfe-von-einride-sieben-eactros-ein/

[90] Use of the ChargePilot charging and energy management system from The Mobility House: https://www.mobilityhouse.com/de_de/unser-unternehmen/presse/artikel/oesterreichische-post-errichtet-modernes-und-intelligentes-ladenetzwerk-mit-the-mobility-house

[91] Use of the ChargePilot charging and energy management system from The Mobility House: https://www.mobilityhouse.com/de_de/unser-unternehmen/presse/artikel/volvo-group-schweiz-ag-setzt-auf-lade-und-energiemanagementsystem-von-the-mobility-house

[92] Use of the ChargEye software from Kempower: https://kempower.com/news/kempower-to-deliver-fast-charging-technology-for-swedens-largest-electric-truck-charging-station/

[93] Use of the Saga software from Einride: https://www.einride.tech/insights/how-to-maximize-the-efficiency-of-electric-freight

[94] Use of the Saga software from Einride: https://www.einride.tech/insights/the-physical-and-digital-infrastructure-behind-intelligent-electric-freight

[95] E-bus radar 2023: https://www.pwc.de/de/branchen-und-markte/oeffentlicher-sektor/pwc-e-bus-radar-2023.pdf

[96] E-bus radar 2022: https://www.pwc.de/de/pressemitteilungen/2022/e-bus-radar-von-pwc-2021-fast-doppelt-so-viele-e-busse-in-deutschland-unterwegs-wie-2020.html

[97] Introduction of e-buses in urban public transport fleets: https://www.sustainable-bus.com/electric-bus/electric-bus-public-transport-main-fleets-projects-around-world/

[98] Charging solutions for e-buses from Kempower: https://kempower.com/news/jonkoping-electric-bus-depot-charging/

[99] Charging solutions for e-buses from ABB: https://new.abb.com/news/detail/85940/abb-powers-progress-for-milans-electric-bus-network

[100] Charging solutions for e-buses from Heliox: https://de.heliox-energy.com/us-case-studies/groesstes-schnellladenetz-fuer-ebusse-in-europa

[101] Charging solutions for electric buses from Irizar: https://www.sustainable-bus.com/news/irizar-schaffhausen-ie-tram/

102 Charging solutions for electric buses from Hitachi Energy: https://www.hitachienergy.com/de/de/about-us/customer-success-stories/grid-emotiontm-to-accelerate-sustainable-mobility-in-london

103 Charging solutions for e-buses from Ekoenergetyka: https://www.electrive.com/2019/08/29/ekoenergetyka-polska-supplies-charging-network/

104 Charging solutions for e-buses from Siemens: https://www.electrive.com/2020/12/15/siemens-to-equip-europes-largest-e-bus-depot-with-charging/

105 Charging solutions for e-buses from Schunk: https://cms.uitp.org/wp/wp-content/uploads/2022/05/ASSURED-Clean-Bus-report_final2.pdf

106 Deployment of e-buses in Aalborg : https://www.electrive.net/2023/02/10/tide-bus-bus-ladepark-mit-124-anschluessen-in-aalborg/

107 Use of e-buses in Aalborg: https://kempower.com/news/kempower-technology-at-aalborg-electric-bus-depot/

108 Use of e-buses in Amsterdam: https://www.electrive.net/2023/05/30/amsterdam-gvb-setzt-auf-lade-tool-von-the-mobility-house/

109 Use of e-buses in Milan: https://www.solarisbus.com/de/presse/fortsetzung-der-bestellungen-aus-mailand-75-elektrisch-betriebene-solaris-busse-fahren-nach-italien-1773

110 Use of e-buses in Aveiro: https://www.sustainable-bus.com/electric-bus/transdev-aveiro-caetanobus-siemens/

111 Deployment of e-buses in Zaragoza: Transport electrification project in Zaragoza with Avanza | Enel X

112 The Mobility House ChargePilot: https://www.mobilityhouse.com/de_de/unser-unternehmen/presse/artikel/elektrobusse-neue-zusatzfunktionen-von-chargepilot

113 The Mobility House Whitepaper "Charging electric buses intelligently": https://25323067.fs1.hubspotusercontent-eu1.net/hubfs/25323067/Whitepaper_Elektrobusse_DE_CH.pdf?utm_campaign=B2B%20Overall%20Whitepaper&utm_medium=email&_hsmi=74039688&utm_content=74039688&utm_source=hs_automation

114 eMIS PRL and arbitrage: https://www.busplaner.de/de/news/elektromobilitaet-e-mobilitaet-bidirektionales-laden-betriebshof-tanken-und-laden_bidirektionales-laden-wie-oepnv-busse-geld-verdienen-koennen-83395.html

115 eMIS PRL and arbitrage: https://emis-deutschland.com/technologie/

116 Jema Energy V2G-enabled charging solution: https://www.jemaenergy.com/en/producto/depot-chargers-electrical-buses-trucks/

117 Bidirectional storage and charging solution from Ebusco : https://www.electrive.net/2023/10/06/neue-bidirektionale-speicher-und-ladeloesung-von-ebusco/

118 Horrox, Nick et al, 2022, Electric School Buses and the Grid: https://publicinterestnetwork.org/wp-content/uploads/2022/04/FG-Electric-school-buses-and-the-grid.pdf

119 Charging infrastructure solutions for bidirectional charging from Nuvve: https://nuvve.com/wp-content/uploads/2022/04/nuvve-school-bus-packet_lcfs_april2022.pdf

120 AMELIE 2 project: https://www.ikem.de/projekt/amelie-2/

121 E|MPOWER project: https://www.faps.fau.de/neuigkeit/17-11-2022-neues-gemeinschaftsprojekt-empower-demonstriert-dynamisches-laden-von-elektrofahrzeugen-auf-deutschen-autobahnen/#:~:text=%E2%80%9CThe%20project%20E%7CMPOWER%20is%20to%20position%20the%20area%20of%20production%20technology.

[122] UniSwap HD project: https://www.tu.berlin/fvb/forschung/laufende-projekte/uniswaphd

[123] enERSyn project: https://www.ifeu.de/projekt/enersyn-dynamisches-laden-im-kontext-der-lkw-antriebswende

[124] Project evTrailer2: https://www.electrive.net/2022/11/25/evtrailer2-fokus-auf-e-sattelauflieger-fuer-schwere-lkw/

[125] IDEAL project: https://www.pgs.eonerc.rwth-aachen.de/cms/E-ON-ERC-PGS/Forschung/Projekte/~sxmkr/IDEAL/

[126] MEGA-LADEN project: https://www.mega-laden.de/index.php/de/

[127] HV-MELA-BAT project: https://www.ise.fraunhofer.de/de/presse-und-medien/news/2023/projektstart-hv-mela-bat-hochvolt-megawatt-ladesystem-fuer-schwerlast-und-personenverkehr.html

[128] NEFTON project: https://www.ffe.de/projekte/nutzfahrzeugelektrifizierung-fuer-transportsektor-optimierte-netzanbindung-nefton/

[129] SPIRIT-E project: https://spirit-e.de/

[130] ELMAR project: https://www.baunetzwerk.biz/index.php/pilotprojekt-klimaneutraler-steinbruch

[131] BDL final report: https://www.ffe.de/wp-content/uploads/2023/03/BDL-Abschlussbericht.pdf

[132] Potential analysis of bidirectional charging: https://issuu.com/nrw_energy4climate/docs/potenzialanalyse_bidirektionales_laden_final

[133] eGLM project: https://www.eglm.eu/de/eGLM

[134] NextETRUCK project: https://nextetruck.eu/

[135] NextETRUCK – Use case, mission and overall vehicle definition: https://nextetruck.eu/wp-content/uploads/2023/10/NextETRUCK-D2.1-Use-case-mission-and-overall-vehicle-definition.pdf

[136] Living Lab Heavy Duty Laadpleinen: https://rwsduurzamemobiliteit.nl/praktijk/vergroenen/living-lab-heavy-duty-laadpleinen/

[137] KoLa project: https://www.hochbahn.de/de/projekte/elektro-busbetriebshoefe/das-projekt-koordinierungsfunktion-und-lastmanagement

[138] ELINA project: https://www.electrive.net/2022/12/16/balingen-projekt-zu-induktivem-laden-waehrend-der-fahrt/

[139] ASSURED project: https://assured-project.eu/storage/files/d114-d115-final-use-case-demo-brochure_2.pdf

[140] First Student e-buses North America: https://firststudentinc.com/innovation/electric-school-buses/

[141] Kevin Matthews, Process Overview and Unique Considerations For Deploying Commercial Fleet Infrastructure for a School Bus Fleet, presentation at EVS36 in Sacramento in June 2023

[142] "Smart and bidirectional charging of commercial vehicles - R&D Projects and practical applications", Dirk Kaminski, Expert Knowledge Exchange of the Accompanying Research "Elektro-Mobil" on 21 June 2023

[143] Will, Ocker et al, 2022, Flexibility marketing options for charging processes of electric medium-duty and heavy-duty commercial vehicles: https://tennet-drupal.s3.eu-central-1.amazonaws.com/default/2022-11/Daimler%20Truck%20TenneT%20Feasibility%20Study.pdf