



Review

# Review and Evaluation of Automated Charging Technologies for Heavy-Duty Vehicles

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**Abstract:** Automated charging technologies are becoming increasingly important in the electrification of heavy road freight transport, especially in combination with autonomous driving. This study provides a comprehensive analysis of automated charging technologies for electric heavy-duty vehicles (HDVs). It encompasses the entire spectrum of feasible technologies, including static and dynamic approaches, with each charging technology evaluated for its advantages, potentials, challenges and technology readiness level (TRL). Static conductive charging methods such as charging robots, underbody couplers, or pantographs show good potential, with pantographs being the most mature option. These technologies are progressing towards higher TRLs, with a focus on standardization and adaptability. While static wireless charging is operational for some prototype solutions, it encounters challenges related to implementation and efficiency. Dynamic conductive charging through an overhead contact line or contact rails holds promise for high-traffic HDV routes with the overhead contact line being the most developed option. Dynamic wireless charging, although facing efficiency challenges, offers the potential for seamless integration into roads and minimal wear and tear. Battery swapping is emerging as a practical solution to reduce downtime for charging, with varying levels of readiness across different implementations. To facilitate large-scale deployment, further standardization efforts are required. This study emphasizes the necessity for continued research and development to enhance efficiency, decrease costs and ensure seamless integration into existing infrastructures. Technologies that achieve this best will have the highest potential to significantly contribute to the creation of an efficiently automated and environmentally friendly transport sector.

**Keywords:** heavy-duty vehicles; transport electrification; automated charging; technology readiness level



**Citation:** Piedel, E.; Lauth, E.; Grahle, A.; Göhlich, D. Review and

Evaluation of Automated Charging Technologies for Heavy-Duty Vehicles.

*World Electr. Veh. J.* **2024**, *15*, 235.

[https://doi.org/10.3390/](https://doi.org/10.3390/wevj15060235)

[wevj15060235](https://doi.org/10.3390/wevj15060235)

Academic Editor: Ayman EL-Refai

Received: 9 April 2024

Revised: 21 May 2024

Accepted: 22 May 2024

Published: 29 May 2024



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## 1. Introduction

In 2021, a total of 740 million tonnes of carbon dioxide (CO<sub>2</sub>) was emitted by the road transport in the European Union (EU). Whereas the largest share of CO<sub>2</sub> emissions was produced by passenger vehicles and motorcycles, 27% resulted from transport by means of heavy-duty vehicles (HDVs), such as heavy-duty trucks (HDTs) and buses [1]. From 1990 to 2019, the annual CO<sub>2</sub> emissions of HDVs increased by 28%, driven by an increase in haulage capacity, which in turn is linked to economic growth [1,2]. To limit the effects of climate change, the EU introduced CO<sub>2</sub> targets for newly registered HDVs in 2019. These targets require a 15% decrease in the average CO<sub>2</sub> emissions in 2025 and a 30% decrease in 2030, with each target relating to the CO<sub>2</sub> emissions of 2019/2020 [3]. In October 2023, the EU Environment Council voted for a tightening of these targets. According to the council, the CO<sub>2</sub> emissions of HDVs should be reduced by 45% in 2030 and 90% in 2040. For city buses, the council decided on a decrease of 85% in 2030 and 100% in 2035 [4].

To fulfill the original 2030 target, 4% to 22% of the newly registered HDVs have to be zero-emission vehicles, e.g., battery electric vehicles (BEVs) [3]. The usage of BEVs not only reduces CO<sub>2</sub> emissions, but also improves air quality, reduces noise emissions and decreases oil dependency [5]. The acceptance and the success of BEVs depend, inter alia, on the installation of an adequate and scalable charging infrastructure [6,7].

A mobility trend besides decarbonization is automation. Automated road transport has the potential to reduce or shift the labor costs, enable automated (un-)loading, decrease the number of accidents resulting from human error and facilitate new modes of operation, such as reducing driving speed and thereby reducing fuel consumption and emissions. However, low-cost automated transport can result in an increase in transport and in a shift in means of transport, which can rapidly be automated, but are not necessarily sustainable [8]. Consequently, the aim must be to establish prerequisites for the automation of electric HDVs. It is obvious that automated electric HDVs require automated charging technologies.

When advancing the research and development of automated electric commercial vehicles, it is essential to establish a thorough overview of the extant automated charging technologies, while also evaluating their readiness for implementation and giving recommendations for their further development. To the best of the authors' knowledge, there is no such comprehensive compilation and analysis available at the present time. Consequently, this study seeks to answer the following research question:

*Which automated charging technologies for heavy-duty vehicles are currently in development, and what is their present level of technological maturity?*

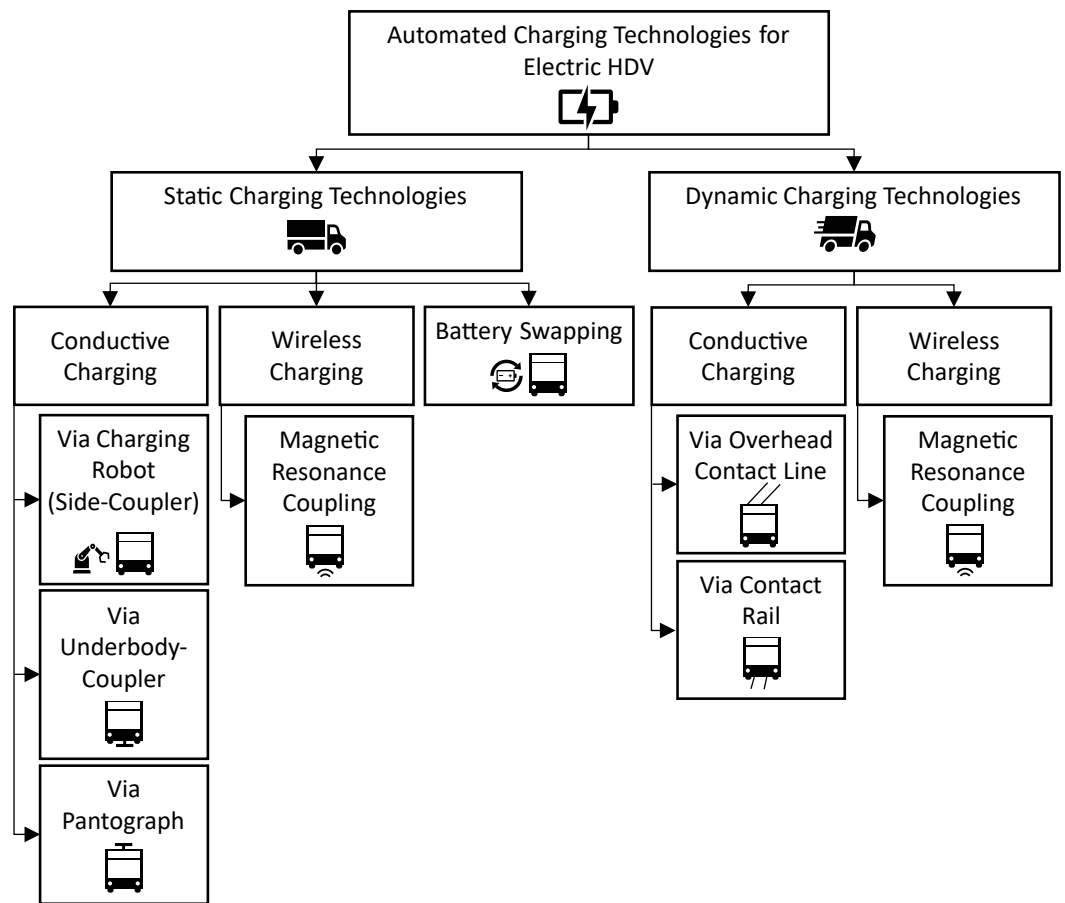
To answer this question, this study investigates the automated charging technologies which have already been commercialized or are currently under development for electric HDVs. Technologies identified include static conductive charging technology using a charging robot, an underbody coupler or a pantograph, static wireless charging technology, battery swap technology, dynamic conductive charging technology using an overhead contact line or contact rails, and dynamic wireless charging technology. This article analyzes the functioning, the advantages, the potentials and the challenges of each charging technology, focusing on aspects such as vehicle adaptations, infrastructure, operation, technological readiness and standardization. Furthermore, this study examines ongoing and future projects, and available market solutions to assign a TRL to each charging technology. The aim of this article is to give an overview of the automated charging technologies for electric HDVs.

### *Classification of Charging Technologies*

According to most of the literature, the automated charging technologies for electric HDVs can be categorized into static and dynamic charging technologies [6,9–15]. Whereas static charging technologies require the vehicle to have come to a standstill before the charging commences, dynamic charging technologies permit the vehicle to be charged while moving. The static and dynamic charging technologies can be further classified by the method of energy transfer from the grid to the vehicle battery. Possible methods are conductive charging, wireless charging and battery swapping [6]. The classification outlined above is illustrated in Figure 1.

Conductive charging requires a physical, electrically conductive connection between the vehicle battery and the battery charger, and can be realized with both static and dynamic charging technologies. Static conductive charging technologies implement the connection by means of charging cables, underbody couplers and pantographs. Dynamic conductive charging technologies apply pantographs and contact arms, and are classified by the type of interface with the infrastructure, which can be an overhead contact line or a contact rail [9]. To automate a conductive charging technology, an automatic connection device must be installed on the side of either the vehicle or the infrastructure to overcome the distance between the vehicle and the charger [6,16]. Whereas the pantograph, the underbody coupler

and the contact arm serve as both the connection and the connection device, the charging cable requires a robot to be plugged in and unplugged [17].



**Figure 1.** Classification of automated charging technologies for electric HDVs.

Wireless charging is the second method to transfer energy from the grid to the vehicle battery. In contrast to conductive charging, it does not require a physical connection between the vehicle and the charger, but rather transfers energy through an electromagnetic wave traveling from a transmitter to a receiver [11,18]. The transmitter is connected to the current source and the receiver is coupled with the load, in this case the vehicle battery [18]. The wireless charging technologies for BEVs utilize the magnetic field of the electromagnetic wave and can be both static and dynamic [9,18].

The third option to transfer energy to the vehicle is battery swapping. This charging technology necessitates a battery swapping station to exchange the depleted battery for a charged battery [19].

This paper is structured as follows: Section 2 presents each of the charging technologies and maps the charging technologies with TRLs. Section 3 discusses the results and draws conclusions.

## 2. Description, Analysis and TRL Determination of Automated Charging Technologies for Electric Heavy-Duty Vehicles

This section examines the functioning and the set-up of leading and emerging automated charging technologies for electric HDVs. Additionally, it explores the advantages, the potentials, the challenges and the development status of each charging technology. This information is then used to determine a specific TRL for each charging technology. The TRLs constitute a TRL scale, which was originally developed by the National Aeronautics and Space Administration (NASA) and is the most widely used tool to assess and compare the maturity of technologies [20]. The TRL scale designed by NASA was adopted

by the EU for its research and innovation funding program Horizon2020. The emerging EU Horizon2020 TRL scale is employed in this study [20,21]. To map each charging technology with a TRL, the current development statuses of exemplary charging systems are investigated. The list of examples for each charging technology is not exhaustive.

## 2.1. Static Charging Technologies

### 2.1.1. Static Conductive Charging via Charging Robot

The static conductive charging technology utilizing a charging robot is based on the method of charging with a charging cable, which represents the most advanced and most widely used charging method amongst HDVs [13]. Besides the conductor, this method requires a rectifier and a transformer, which can be located in- and/or outside the vehicle. Depending on the arrangement, the vehicle can be charged with alternating current (AC), direct current (DC) or both alternately [9]. At present, charging powers of up to 43 kW (AC) and 500 kW (DC) are possible [22]. The Megawatt Charging System (MCS) standard currently under development will enable an even higher charging power of more than 1 MW [23].

When charging with a charging cable, a communication system and protection measures are required. DC charging can additionally demand a temperature management system [9].

To automate charging with a charging cable, a robot can be placed at the charging station. The robot is equipped with a camera-based object detection system, which detects and identifies the vehicle to receive vehicle-specific data, such as the position of the charging socket and the required charging power. Based on this information, the charging robot first aligns the charging plug with the charging socket, then inserts the plug into the socket and finally removes the plug from the socket. The robot's accuracy depends on the accuracy of its vision, control and motion systems, the components' tolerance ranges and the current temperature, vibrations and environmental conditions. The operating range of the charging robot and the installed charging plug determine the chargeable vehicle types and the possible socket locations. To enable mobile charging, the robot can be mounted on a movable platform or an automated vehicle [22].

A summary of the advantages, the potentials and the challenges of static conductive charging technology using a charging robot is given in Table 1.

Besides being based on a widespread charging method, static conductive charging technology using a charging robot has the advantage that it does not entail extra vehicle components, which would result in extra costs, extra weight and extra space requirements [13,16]. Additionally, standards for conductive charging using a robot are under development, e.g., IEC TS 61851-27 ED1 [24], and the charging technology has the potential to use the already developed standards for manual charging with a cable. Furthermore, due to the set-up of the charging system, it is not limited to electric HDVs, there is the possibility for a mobile charging robot and the potential to gradually scale up the charging infrastructure in parallel to the scale-up of the BEVs [11,22].

The charging technology faces various challenges. First, it requires a parking area designed for charging. Second, the charging robot requires additional space [16]. Third, both the charging robot and the charging process are conspicuous [6,16]. Fourth, the charging technology necessitates maintenance and repair expenses of the moving and connecting parts [6]. Moreover, the connected parts result in any movements of the vehicle, e.g., when (un-)loading, being transmitted to the robot. Fifth, due to its positioning beside the parking area, the charging infrastructure is susceptible to accidental damage and misuse [16]. Further challenges are the charging-related vehicle downtime, which depends on the charging power and the battery system, and the need for standards for the location, the orientation, the (security) cover, and the opening and closing mechanism of the charging socket. The parking position and the vehicle payload, the tire pressure and the springs and dampers scenario also influence the socket position [25]. The robot's operating range determines the parking requirements. Additional challenges are the developed charging interface,



e.g., the shape of the plug and the socket, not being well suited for automation and the robot's camera-based socket detection system being susceptible to lighting and surface conditions [22]. Finally, the charging cables represent a safety hazard and a challenge regarding handling, especially the heavy and stiff cables used for high-power charging [7,25]. To ensure the safety of the users, collaborative robots are necessary [26].

**Table 1.** Summary of the static conductive charging technology using a charging robot (SCR).

Category	Advantages and Potentials	Challenges
<i>Vehicle adaptations</i>	<ul style="list-style-type: none"> <li>No additional vehicle components necessary</li> </ul>	
<i>Infrastructure</i>	<ul style="list-style-type: none"> <li>Possibility for gradual scale-up of charging infrastructure in parallel to scale-up of BEVs</li> </ul>	<ul style="list-style-type: none"> <li>Specific parking area required for charging</li> <li>Additional space requirements for charging robot</li> <li>Conspicuous charging robot and charging process</li> </ul>
<i>Operation</i>	<ul style="list-style-type: none"> <li>Not limited to electric HDVs</li> </ul>	<ul style="list-style-type: none"> <li>Vehicle downtime depending on charging power and battery system</li> <li>Susceptible to accidental damage and misuse</li> <li>Maintenance and repair expenses of moving and connecting parts</li> <li>Parking requirements depend on charging robot's operating range</li> </ul>
<i>Technological readiness and standardization</i>	<ul style="list-style-type: none"> <li>Based on widespread and standardized charging method using cable</li> <li>Standards for conductive charging using robot under development</li> </ul>	<ul style="list-style-type: none"> <li>Current charging interface design not well suited to automation</li> <li>Not yet commercialized; prototypes undergoing testing</li> </ul>
<i>Miscellaneous</i>	<ul style="list-style-type: none"> <li>Possibility for mobile charging robot</li> </ul>	<ul style="list-style-type: none"> <li>Need for standardized socket location, orientation, cover, opening and closing mechanism, and security cover</li> <li>Camera-based socket detection system susceptible to lighting and surface conditions</li> </ul>

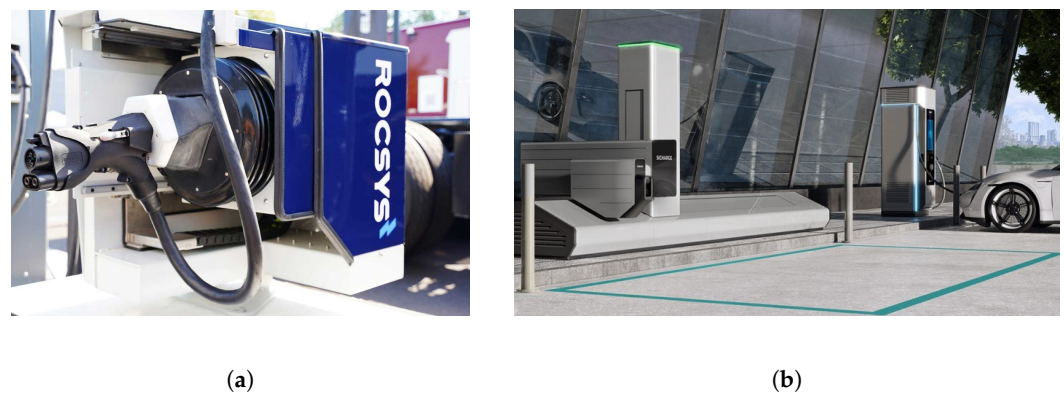
The Charging technology using a charging robot is currently being developed for use in electric HDVs. Three examples of developing companies including their charging systems (see Figure 2) are presented below.

- ROCSYS:** In 2021, ROCSYS together with the companies Grivix and VDL ETS developed a charging robot to automate the static conductive charging of electric HDVs [27]. To integrate the robot into existing systems, ROCSYS offers, inter alia, an automated socket cover, a communications unit and an interface to control and monitor the robot [28]. The charging robot is equipped with a Combined Charging System (CCS), a Megawatt Charging System or an Euro-Din charging plug and a 3D camera, and is not limited to specific vehicle or charger types [28,29]. In 2021, ROCSYS' charging robots were employed by the companies eVersum and Ebusco to automate the charging of electric shuttles and buses [30,31]. In 2022, the robots were installed at a public charging station for electric medium- and heavy-duty vehicles in Portland, OR, USA, and at the Oakland Harbor, CA, USA, where they charge tractors operated

by the firm SSA Marine [32,33]. The charging station is managed by Daimler Truck North America and Portland General Electric and contains 12 charging points [33]. In 2023, ROCSYS partnered with the companies Taylor Machine Works and Hyster to automate the charging of electric container handlers and terminal tractors [34,35].

- **Siemens:** In 2021, Siemens presented a prototype of an automated charging station for BEVs. This charging station incorporates a charging robot, which connects to the CCS socket of the vehicle using optical sensors and artificial intelligence in around one minute. The vehicle is charged with a power of up to 300 kW. The charging station was tested in cooperation with the truck manufacturer EINRIDE. To fulfill the requirements of the end-users successive charging stations will have a charging power of up to 1 MW [36].
- **Stäubli:** The QCC system developed by the company Stäubli enables automated charging of BEVs, such as electric trucks and buses [37]. The charging system includes an automatic charging device placed beside the vehicle and a corresponding socket, which is installed in the vehicle [38]. The QCC system can supply a charging power of more than 1 MW. Additionally, it can correct for misalignment, is equipped with a self-cleaning mechanism and is especially designed for challenging operating conditions, for example in mines and ports [37,39]. In 2023, Stäubli provided its charging systems to the company SSA Terminals, LLC to charge 33 terminal tractors at the Port of Long Beach, CA, USA. Five additional charging systems were installed at the Port of Oakland, CA, USA [39].

In the evaluation of the TRL, the 2023 partnership between ROCSYS and Hyster stands out as a key determinant. In this context, the system is actively demonstrated and further enhanced with a particular focus on performance in challenging environments [35]. This endeavor, along with several preceding projects, suggests a progression to a TRL 7, which is indicative of a system prototype's demonstration in an operational setting. The QCC system developed by Stäubli is also being demonstrated in an operational environment [39]. The Autonomous Charging System developed by Siemens was tested in collaboration with the truck manufacturer EINRIDE. This points to a TRL 6, confirming that the technology has been demonstrated in a relevant environment [36].



**Figure 2.** Examples of static charging technology using a charging robot: (a) ROCSYS' charging robot: ROC-1 (reproduced with permission from ROCSYS B.V.). (b) Rendering of Siemens' Autonomous Charging System (reproduced with permission from Siemens AG).

### 2.1.2. Static Conductive Charging via Underbody Coupler

As can be seen in Figure 1, static conductive charging technologies can be categorized into side-coupling, underbody-coupling and over the vehicle's roof coupling systems. This subsection focuses on the underbody-coupling systems.

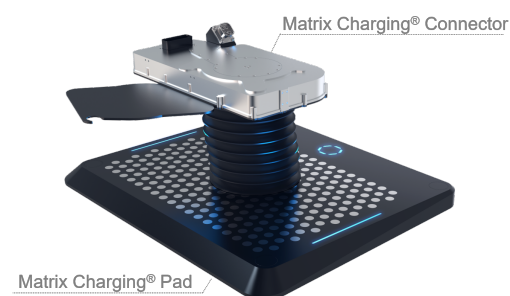
An underbody-coupling system consists of a fixed or a movable ground unit and a fixed or a movable vehicle unit. Whereas the ground unit is embedded in or placed on the surface of the charging station, the vehicle unit is attached to the underbody of the vehicle. To charge the vehicle, the ground unit and the vehicle unit must be aligned [22]. The extent

of possible misalignment depends on the specific charging system. However, a benchmark is set at  $\pm 150$  mm from the optimal parking position along the vehicle's longitudinal and transversal axes. To maximize the parking accuracy, assistance systems can be employed. As soon as the ground unit and the vehicle unit are aligned, their electrical interfaces must be physically connected [16]. For this, the connector of the movable unit moves onto the fixed unit and in doing so can be assisted by a specific interface layout and guided by magnetic, visual or ultra-sound systems [22]. Besides the ground unit and the vehicle unit, the charging technology requires a rectifier, a transformer, a communication system and a management system to monitor and control the charging process [40].

A summary of the advantages, the potentials and the challenges of the static conductive charging technology using an underbody coupler is presented in Table 2.

In comparison to charging technology using a charging robot, charging technology employing an underbody coupler requires no additional space for its charging infrastructure, as it is installed underneath the parking vehicle. As the charging process takes place unseen underneath the vehicle and the ground unit can be embedded in the road pavement, charging technology using an underbody coupler is also less conspicuous. If both the ground unit and the vehicle unit are additionally equipped with protective covers, the charging technology is also less susceptible to accidental damage and misuse [16]. In comparison to charging technology using a robot, charging technology employing an underbody coupler is not based on a widespread, standardized and manual charging method, resulting in it being wholly designed for automation. Further advantages and potentials are the standards, e.g., IEC TS 61851-26 ED1 [41], which are already being developed, the fact that the charging technology is not limited to electric HDVs and the possibility for a mobile ground unit. Additionally, there is the potential to gradually scale up the charging infrastructure in parallel to the scale-up of the BEVs.

In contrast to side-coupling systems, underbody-coupling systems require additional vehicle components [16]. In the case of a movable ground unit, the vehicle unit can be small, lightweight, simple and easy to integrate, which reduces the negative effects of additional vehicle components [42]. However, in this case, complex robotic kinematics and control systems are required [22]. If the ground unit is fixed and implemented as a pad, misalignment of the vehicle unit can be corrected without requiring moving parts. Such a charging system was developed by the company Easelink (see Figure 3). The ground unit in the shape of a pad is equipped with a multitude of contact points that can be individually switched on and off. The connector of the vehicle unit must only perform a vertical movement to connect to the pad. As only one degree of freedom is required, the connector's complexity, cost, maintenance and repair expenses, and space requirements are reduced. Additionally, the high space availability of the ground area is used [16,22,40]. Further challenges are the specific parking area required for charging, the charging-related vehicle downtime, the maintenance and repair expenses of the moving and connecting parts and the need for standardization of the charging interface. Additionally, the necessary parking accuracy is higher than that required for charging with a robot [22].



**Figure 3.** Rendering of Matrix Charging System developed by Easelink (reproduced with permission from Easelink GmbH).

**Table 2.** Summary of static conductive charging technology using an underbody coupler (SCU).

Category	Advantages and Potentials	Challenges
<i>Vehicle adaptations</i>		<ul style="list-style-type: none"> <li>• Additional underbody charging interface necessary</li> </ul>
<i>Infrastructure</i>	<ul style="list-style-type: none"> <li>• Possibility for gradual scale-up of charging infrastructure in parallel to scale-up of BEVs</li> <li>• In comparison to SCR (Table 1), no additional space requirements for charging infrastructure</li> <li>• In comparison to SCR (Table 1), less conspicuous charging infrastructure and charging process</li> </ul>	<ul style="list-style-type: none"> <li>• Specific parking area required for charging</li> </ul>
<i>Operation</i>	<ul style="list-style-type: none"> <li>• Not limited to electric HDVs</li> <li>• In comparison to SCR (Table 1), less susceptible to accidental damage and misuse</li> </ul>	<ul style="list-style-type: none"> <li>• Vehicle downtime depending on charging power and battery system</li> <li>• Maintenance and repair expenses of moving and connecting parts</li> <li>• In comparison to SCR (Table 1), higher parking accuracy required</li> </ul>
<i>Technological readiness and standardization</i>	<ul style="list-style-type: none"> <li>• Charging technology specifically designed for automation</li> <li>• Standards for conductive charging using underbody coupler under development</li> </ul>	<ul style="list-style-type: none"> <li>• Not based on widespread and standardized charging technology</li> <li>• Not yet commercialized; prototype tests pending</li> </ul>
<i>Miscellaneous</i>	<ul style="list-style-type: none"> <li>• Possibility for mobile charging robot</li> </ul>	<ul style="list-style-type: none"> <li>• Need for standardized charging interface location, cover, opening and closing mechanism, and security cover</li> </ul>

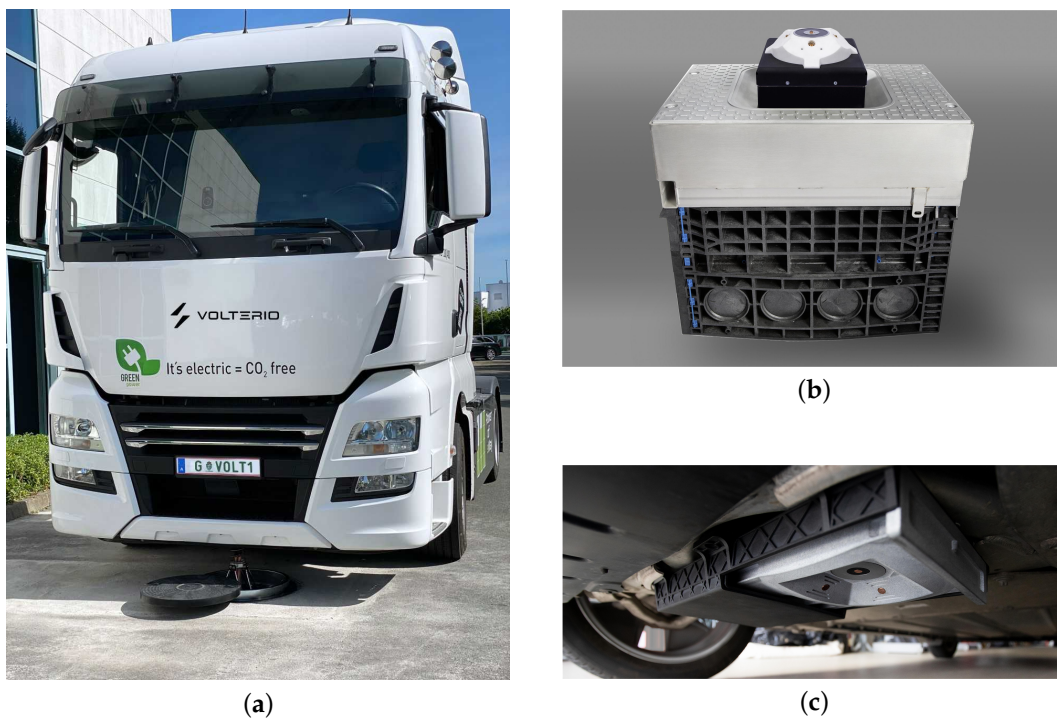
Static conductive charging technology using an underbody coupler is being developed for use in electric HDVs. Four examples of developing companies and research institutions including their charging systems (see Figure 4) are introduced below.

- **Volterio:** The Volterio PRO is an underbody-coupling system developed by the company Volterio to charge electric HDVs. The charging system's ground unit can supply a charging power of up to 2 MW, is embedded in the road pavement, resembles a manhole cover and can withstand being driven over by HDTs. Before charging, the ground unit's cover performs an upwards and then sideways motion to expose a parallel robot, which connects the connector to its counterpart attached to the vehicle's underbody. The charging system enables AC and DC charging and does not require high parking accuracy [43].
- **Fraunhofer Institute for Transportation and Infrastructure Systems IVI:** The underbody-coupling system developed by the Fraunhofer IVI can supply a charging power of up to 2 MW to electric HDVs [44]. The charging system consists of a fixed vehicle unit, which is retrofitted, weighs around 2 kg and is equipped with a protective cover, and a movable ground unit, which is lowered roughly 700 mm into the ground, is equipped with a heating system and a protective cover, and employs an electromagnet to increase the contact force [44–46]. This charging system will be demonstrated, tested and enhanced within the scope of the Mega-Laden Project [47,48].



- **Schunk Transit Systems:** A third prototype is being developed by the company Schunk Transit Systems. Their charging system consists of a movable ground unit, a fixed vehicle unit, and a vehicle positioning and identification system. The prototype can correct parking deviations and is suitable for private and public use [49]. The vehicle battery can be charged with a charging power of up to 1 MW [50].
- **Elonroad:** Besides the charger, the underbody-coupling system developed by the company Elonroad consists of a fixed contact rail and a movable energy collector. The contact rail, which is attached to the ground, is 3.2 m long, 0.25 m wide, 0.04 m high and weighs 50 kg. The energy collector, which is attached to the vehicle's underbody, is 2.25 m long, 0.85 m wide, 0.035 m high and weighs 20 kg. The contact rail currently supplies a charging power of up to 60 kW. In 2024, it will be increased to 150 kW [51]. The underbody-coupling system is being tested by the Swedish company Martin & Servera, where it charges an electric HDT during (un-)loading [52].

The underbody-coupling system developed by Volterio is being tested for electric passenger vehicles within the framework of the AC/DC Project in Graz, Austria. As this charging system is the first of its kind, a TRL 5 is proposed [53]. The TRL 5 indicates that the technology has been validated in a relevant environment. Similarly, the underbody-coupling systems developed by the Fraunhofer IVI and the Schunk Transit Systems company were successfully tested for electric passenger vehicles within the scope of the AULA Project and will be demonstrated for electric HDVs within the framework of the Mega-Laden Project [44,47,48,54]. Therefore, a TRL 5 is also determined for this system for the HDV use case. The underbody-coupling system developed by Elonroad is being tested by an end-user in its operational environment, which indicates a TRL 7 [52].



**Figure 4.** Prototypes of static charging technology using an underbody coupler developed by (a) Volterio (reproduced with permission from Volterio GmbH); (b) Fraunhofer IVI (ground unit) (reproduced with permission from Fraunhofer IVI); (c) Fraunhofer IVI (vehicle unit) (reproduced with permission from Fraunhofer IVI).

### 2.1.3. Static Conductive Charging via Pantograph

The third category of static conductive charging technologies encompasses the over the vehicle's roof coupling systems. These systems employ pantographs to transfer energy from the grid to the vehicle battery [22]. A pantograph can be installed on the side of either the



infrastructure (inverted) or the vehicle (roof mounted) and connects to an interface located on the respective other side. An inverted pantograph can have different interfaces with the vehicle. The most common interface is four contact rails placed in rows of two in parallel on the vehicle's roof. The contact rails entail an additional weight of 15–20 kg. The choice of interface only barely affects the charging parameters [55]. As soon as the vehicle comes to a standstill, the inverted pantograph, which is attached to a mast, is automatically lowered onto the contact rails. Prior to charging, safety checks are performed. Once the battery is fully charged or the charging process is interrupted, the pantograph automatically disconnects from the rails [56]. Based on the SLS201, an inverted pantograph manufactured by the Schunk Transit Systems company, it can be stated that inverted pantographs have a range of 0.7–2.3 m, connect with a force of 500 N and weigh 175–180 kg. The SLS201 is depicted in Figure 5. When employing a roof-mounted pantograph, an additional resting frame, attached to the vehicle's roof, and a contact dome, representing the interface with the infrastructure, are required [55]. In this case, the pantograph is automatically raised once the vehicle comes to a standstill underneath the contact dome [57]. According to the SLS102, a roof-mounted pantograph developed by Schunk Transit Systems, roof-mounted pantographs have a range of 1.5–1.8 m, deliver a force of 250–275 N and weigh 85 kg (see Figure 5) [55].



**Figure 5.** Pantographs developed by Schunk Transit Systems: (a) SLS 201 (reproduced with permission from Schunk Group). (b) SLS 102 (reproduced with permission from Schunk Group).

The pantographs offered by Schunk Transit Systems are equipped with 2-, 3-, 4- or 5-pin connectors, correct parking deviations and vehicle movements of up to  $\pm 500$  mm in driving direction,  $\pm 250$  mm perpendicular to driving direction and  $4^\circ$  kneeling and can be used for depot, opportunity and pulse charging. Additionally, the pantographs manage 400,000 charging cycles and establish a connection within 5 s [50].

Besides the pantograph, the interface and the energy supply, the charging technology requires a communication system and an assistance system, e.g., a passive advanced driver assistance system or road and curb markings, to position the vehicle [55,56,58].

A summary of the advantages, the potentials and the challenges of the static conductive charging technology using a pantograph is given in Table 3.

Similarly to static charging technology using a robot, which is based on conventional charging with a cable, charging technology employing a pantograph is based on the widespread and standardized railway technology [12]. Also, charging technology using a pantograph is similarly susceptible to accidental damage. However, resulting from the charging process occurring out of reach of users, it is less susceptible to misuse. Further advantages and potentials are the already developed standard EN 50696 [59] and the possibility to gradually scale up the charging infrastructure in parallel to the scale-up of BEVs. Finally, the charging technology is specifically designed for automation, which results in a high possible charging power and therefore a reduced charging duration [57].

In contrast to charging technology using a robot, charging technology employing a pantograph requires additional vehicle components. If an inverted pantograph is employed, the negative effects of the additional vehicle components can be reduced [6]. However, if a

roof-mounted pantograph is installed, the infrastructure costs can be decreased and, in the case of the pantograph being damaged, not all vehicles are affected [6,60]. The inverted and the roof-mounted pantograph systems are incompatible [55]. Further challenges are that for safety reasons the connection between the interface and the pantograph can only be established while driving forward and that, due to the layout of the charging technology, it is limited to electric HDVs [58]. Additionally, a specific parking area is required for charging, charging-related vehicle downtime is unavoidable and maintenance and repair expenses of the moving and connecting parts are necessary. In comparison to charging technology using a robot, charging technology employing a pantograph has larger additional space requirements for the charging infrastructure and therefore a more conspicuous charging infrastructure. The charging process, however, is similarly conspicuous.

**Table 3.** Summary of static conductive charging technology using a pantograph (SCP).

Category	Advantages and Potentials	Challenges
<i>Vehicle adaptations</i>		<ul style="list-style-type: none"> <li>• Additional pantograph or contact rails necessary</li> </ul>
<i>Infrastructure</i>	<ul style="list-style-type: none"> <li>• Possibility for gradual scale-up of charging infrastructure in parallel to scale-up of BEVs</li> </ul>	<ul style="list-style-type: none"> <li>• Specific parking area required for charging</li> <li>• In comparison to SCR (Table 1), larger additional space requirements for charging infrastructure</li> <li>• In comparison to SCR (Table 1), more conspicuous charging infrastructure and similarly conspicuous charging process</li> </ul>
<i>Operation</i>	<ul style="list-style-type: none"> <li>• In comparison to SCR (Table 1), similarly susceptible to accidental damage, less susceptible to misuse</li> </ul>	<ul style="list-style-type: none"> <li>• Vehicle downtime depending on charging power and battery system</li> <li>• Maintenance and repair expenses of moving and connecting parts</li> <li>• Limited to electric HDVs</li> <li>• Forward motion necessary for connection</li> </ul>
<i>Technological readiness and standardization</i>	<ul style="list-style-type: none"> <li>• Charging technology specifically designed for automation</li> <li>• Based on widespread and standardized railway technology</li> <li>• Existing standard for conductive charging using pantograph</li> <li>• Commercialized</li> </ul>	
<i>Miscellaneous</i>		<ul style="list-style-type: none"> <li>• Incompatibility of roof-mounted and inverted pantograph systems</li> </ul>

Charging technology using a pantograph has been commercialized. Examples of manufacturers and their market solutions are presented below.

- **Schunk Transit Systems GmbH:** This company offers a variety of pantograph-based charging systems. For example: a roof-mounted pantograph with a charging power of 150 kW to 1 MW, an inverted pantograph for depot charging with a power of up to 200 kW and an inverted pantograph with a charging power of up to 600 kW.

The company's inverted pantographs can connect to contact rails, covers or funnels installed on the vehicles' roofs [50].

- **ABB Ltd.:** The ABB company supplies a roof-mounted and an inverted pantograph, which each deliver a charging power of up to 600 kW and can be used to charge buses of different makes [61,62]. The inverted pantograph is based on a standard called OppCharge [62]. OppCharge was developed by the Volvo Bus Corporation and encompasses a standardized interface in the form of contact rails and a standardized communications protocol, which manufacturers can draw on as long as no international standards have been defined [63].
- **Heliox Energy:** Heliox Energy is a company that acquires pantograph systems and embeds them into designed, constructed, maintained and monitored charging infrastructures for electric buses, trucks, passenger cars and mining, port and marine vehicles [55,64]. For example: Heliox Energy has fitted 31 electric buses in Amsterdam, the Netherlands, three electric buses in Jena, Germany, 55 electric buses in Rotterdam, the Netherlands, 100 electric buses at Amsterdam Schiphol Airport, the Netherlands, and eight electric buses in Cologne, Germany, with roof-mounted pantographs and peripheral components [65–69].

Further companies offering pantograph systems are Siemens and Stemmann Technik [70,71]. Static charging technology using a pantograph is currently being employed by bus operators in eleven German cities [66,69,72]. Examples of manufacturers offering vehicles with the charging technology are Scania, Volvo, Mercedes-Benz and Solaris [73–76].

As presented above, the charging technology is offered by numerous manufacturers, including vehicle manufacturers, and there is extensive, long-term experience from its application in city buses across the world [73–76]. Hence, a TRL 9 is proposed, pointing out that the charging technology is proven in an operational environment. It is important to note that a TRL 9 does not rule out further development in order to address potential challenges.

#### 2.1.4. Static Wireless Charging

The next static charging technology to be examined more closely is wireless charging technology. Wireless charging of BEVs can be realized with a variety of coupling techniques with the most developed and widespread being the magnetic resonance coupling technique [9,18]. A charging system applying this technique encompasses a wallbox, including a rectifier and a high-frequency inverter, a ground unit, a vehicle unit, an onboard charger, including a rectifier and a transformer, and a battery management system [9,10]. The wallbox is connected to the electricity grid and has the task of increasing the frequency of the AC, as a high frequency results in high efficiency. From there, the energy is transmitted to the ground unit, which is embedded in the road pavement and contains a primary coil [9,15,77]. When the high-frequency AC flows through the primary coil, it generates an alternating magnetic field. This passes through the secondary coil, located opposite the primary coil in a vehicle unit attached to the vehicle's underbody, where it induces an alternating voltage [9,13,15]. The resulting AC is rectified by the onboard charger, before being used to charge the vehicle battery [9]. Besides the coils, both the vehicle unit and the ground unit contain shielding materials, elements to optimize the magnetic flux distribution and compensation networks. These networks are composed of reactive components such as capacitors and have the task of matching the resonant frequencies of the primary and the secondary coil to the frequency of the alternating magnetic field. As a result, the charging system's degree of efficiency and the transmission distance are increased [10,18,78,79]. Furthermore, the magnetic leakage flux resulting from the distance between the coils is compensated, which increases the degree of efficiency further [9].

Wireless charging requires the use of a wireless communication system and a foreign object detection system [9,15]. The latter has the task of detecting foreign objects located between the vehicle unit and the road pavement, as they not only reduce the charging system's efficiency but might also present a safety risk, due to induced currents and subsequent warming [9,18]. Furthermore, living object protection systems can be employed

in areas where the electromagnetic compatibility (EMC) requirements cannot be met, which are, however, accessible to living objects. These systems automatically reduce the charging power in case of a living object penetrating a respective area [9].

A summary of static wireless charging technology's advantages, potentials and challenges is given in Table 4.

**Table 4.** Summary of static wireless charging technology (SCW).

Category	Advantages and Potentials	Challenges
<i>Vehicle adaptations</i>		<ul style="list-style-type: none"> <li>• Additional vehicle unit necessary</li> </ul>
<i>Infrastructure</i>	<ul style="list-style-type: none"> <li>• Possibility for gradual scale-up of charging infrastructure in parallel to scale-up of BEVs</li> <li>• No additional space requirements for charging infrastructure</li> <li>• In comparison to SCR (Table 1), less conspicuous charging infrastructure and charging process</li> </ul>	<ul style="list-style-type: none"> <li>• Specific parking area required for charging</li> </ul>
<i>Operation</i>	<ul style="list-style-type: none"> <li>• Not limited to electric HDVs</li> <li>• In comparison to SCR (Table 1), SCU (Table 2) and SCP (Table 3), less maintenance and repair expenses</li> </ul>	<ul style="list-style-type: none"> <li>• Vehicle downtime depending on charging power and battery system</li> <li>• In comparison to SCR (Table 1), less susceptible to accidental damage and misuse</li> <li>• Efficiency depends on horizontal misalignment and vertical distance between coils</li> <li>• In comparison to SCR (Table 1), higher parking accuracy required</li> </ul>
<i>Technological readiness and standardization</i>	<ul style="list-style-type: none"> <li>• Charging technology specifically designed for automation</li> <li>• Existing standards for static wireless charging</li> <li>• Commercialized</li> </ul>	<ul style="list-style-type: none"> <li>• Not based on widespread and standardized charging technology</li> </ul>
<i>Miscellaneous</i>	<ul style="list-style-type: none"> <li>• Possibility for mobile ground unit</li> </ul>	

In comparison to static conductive charging technologies, static wireless charging technology has the advantage that it does not require any moving and connecting parts. Consequently, the maintenance and repair expenses are reduced [9]. Additionally, wireless charging technology can draw on already developed standards, e.g., IEC 61980-1 [80]. Further advantages are the facts that the charging technology is not limited to electric HDVs, that it is specifically designed for automation and that it requires no additional space for its charging infrastructure. In comparison to charging technology employing a robot, wireless charging technology is less conspicuous and less susceptible to accidental damage and misuse [9]. Finally, there is the potential to gradually scale up the charging infrastructure in parallel to the scale-up of the BEVs and the possibility for a mobile ground unit [11].

With these advantages and potentials come challenges. First, additional vehicle components are necessary [9]. Second, a specific parking area is required for charging. Third, in comparison to charging technology using a robot, higher parking accuracy is required. Fourth, the charging efficiency depends on the horizontal misalignment and the

vertical distance between the coils [22]. To combine high efficiency and great distance, there is the possibility of lowering the vehicle unit ahead of charging. This, however, entails the challenges of moving parts [9]. The efficiency of the charging system can be increased further by employing a parking assistant, ferrite plates in both units, a large secondary coil, special coil designs and geometries, and a variable transmission frequency [9,10,18]. Also, the ground clearance and the loading condition of an electric HDV affect the distance between the coils and thereby the efficiency [14]. Further challenges are the charging-related vehicle downtime and the fact that wireless charging technology cannot build on a widespread and standardized charging method.

As can be seen from Table 4, static wireless charging technology has been commercialized. A selection of manufacturers is introduced below.

- **InductEV:** This company develops static wireless charging systems for private, public and commercial transport vehicles, port vehicles and industrial equipment [81]. This charging system encompasses modular charging pads, which can supply 50 kW (one pad)–450 kW (six pads) of charging power with an efficiency of over 90 % and a response time of 2 s (see Figure 6) [82,83]. Currently, 115 vehicles linked to twelve customers are equipped with InductEV’s charging system and are in operation [84]. Customer examples are Gillig, BYD, Kansas City International Airport, IndyGo, Link Transit, OshKosh and Green Power Motor Company [82,83].
- **Electreon:** Electreon offers both static and dynamic wireless charging technology with the static charging technology being commercially deployed since 2022. In 2022, the static charging systems were installed at city bus stops across Israel to charge 200 electric buses, following a successful pilot project at the Tel Aviv University train station in Israel [85]. By order of a second Israeli bus operator, Electreon will fit 30 more buses with their static wireless charging technology to charge at a bus depot in 2023 [86]. Also in 2023, Electreon will install two wireless charging points for an electric bus in Balingen, Germany, following a second pilot project in Karlsruhe, Germany [87].
- **WAVE Charging:** This company offers static wireless charging technology to charge electric medium- and heavy-duty vehicles during scheduled stops and dwell times. The charging technology can deliver a charging power of 125–500 kW with an efficiency of up to 92 %. The company has deployed its charging technology in six locations across the USA [88].
- **WiTricity:** WiTricity’s static charging technology supplies a charging power of 3.6–22 kW with an efficiency of 90–93 % over an air gap of 100–250 mm. Additionally, it offers the possibility for bidirectional energy transfer [89].



**Figure 6.** Static wireless charging system developed by InductEV for an electric bus: (a) ground unit (two charging pads) (reproduced with permission from InductEV Inc.). (b) Vehicle unit (four charging pads) (reproduced with permission from InductEV Inc.).

Concerning the technological readiness of the static wireless charging technology, the announced commercial deployment of the charging system developed by Electreon



indicates a TRL up to 9 [85]. Additionally, the charging system developed by the company InductEV is offered as a factory option by the bus manufacturer BYD in the USA [90]. However, as acquiring a CE marking is still underway, a TRL 8–9 is suggested [81]. Owing to the high number of deployments across the USA, a minimum TRL 7 is proposed for the charging system developed by the company WAVE Charging [88]. In 2023, WiTricity announced a collaboration with a Chinese manufacturer of autonomous buses. As the company's charging system has previously only been installed in passenger vehicles, a TRL 5 is suggested [91]. Although there is a strong deviation between the TRLs of the different manufacturers, a higher TRL for static wireless charging can be determined by the commercial availability of the systems of some manufacturers. Overall, a TRL between 8 and 9 is identified. As mentioned above, a high TRL does not exclude further development of the charging technology in order to address potential challenges.

### 2.1.5. Battery Swapping

Besides conductive and wireless charging, there is the possibility to swap the depleted battery for a fully charged battery in a battery swapping station (BSS) [19]. The battery swap technology, therefore, both temporally and spatially decouples the battery charging from the BEV and its driving patterns. Generally, there are two types of BSSs:

1. **Centralized:** The swapping and the charging occur in different locations. The depleted batteries are collected from multiple BSSs and then charged in one location.
2. **Distributed:** The swapping and the charging occur in the same location. The depleted batteries are charged in the corresponding BSSs [92].

Irrespective of the type of BSS, the main components of a BSS are the swapping robots, the battery storage racks, the battery charging racks, the chargers, the batteries, the rectifiers, the transformers, and the management and control systems.

The swapping process begins with the BSS receiving a swapping request from a vehicle. This includes the vehicle's current position, its expected time of arrival and battery- and vehicle-specific data, which enable the BSS to prepare a fitting battery. Once the vehicle arrives at the BSS, the driver is identified, authenticated and then guided to the swapping lane [19]. There, the removing and the reinstalling of the battery is performed by one or two robots [92]. Either way, the battery is dismounted from the side, the rear, the underbody or the roof of the vehicle, while the vehicle is stationary or moving [19]. Once removed, the battery is placed in the charging rack if necessary via a storage rack [92]. Before the charging of the battery begins, its state of charge (SOC), state of health (SOH), remaining charge, age, and number of charge and discharge cycles are determined. Then, depending on the demand, the battery is charged with a low or a high charging power. Normally a BSS works according to the "first come, first served" principle. The communication between the vehicle and the BSS takes place via an information system. For example, the information system receives the vehicle's swapping request and transmits it to the BSS [19]. The multitude of batteries charged in one location necessitates an extensive temperature management system and additional safety measures [92,93].

A summary of the advantages, the potentials and the challenges associated with battery swap technology is given in Table 5.

The main advantage of the battery swap technology is that the battery swapping can be performed within five minutes [19]. It thereby overcomes one of the major drawbacks of BEVs, namely the relatively long charging time compared to refueling with diesel. The second advantage is that the BSS has a flexible energy demand, meaning its energy demand does not necessarily depend on the consumer demand for battery swaps. This reduces the investments in power lines, storage systems and power generation capacities [94]. If the consumer demand is low or back-up batteries are available, the batteries can be charged with a low charging power during off-peak hours, which also reduces the electricity costs, increases the battery lifetimes and flattens the load curve [13,19,94]. During peak hours the batteries can feed energy into the grid to generate revenue [19]. With the battery swapping decoupled from the battery charging, pricing might present a challenge [95]. Further

advantages are the existing standards, e.g., IEC 62840-2 [96], and the fact that the battery swapping is performed within an enclosed area, which ensures that the swapping and the charging systems are less exposed to the environment, accidental damage and misuse than the other static charging technologies. Also, the battery swap technology is not limited to electric HDVs. However, to the best of the authors' knowledge, there is no BSS that is used to swap the batteries of both passenger vehicles and HDVs. Another potential is that the reinstalled battery can be chosen according to the user's needs and preferences regarding, e.g., capacity [92]. Finally, there is the fact that the battery swap technology is mostly designed for automation.

**Table 5.** Summary of battery swap technology (BS).

Category	Advantages and Potentials	Challenges
<i>Vehicle adaptations</i>		<ul style="list-style-type: none"> <li>• Need for additional standardized BSS–battery–vehicle interface</li> </ul>
<i>Infrastructure</i>		<ul style="list-style-type: none"> <li>• Limited possibility to scale up charging infrastructure in parallel to scale-up of BEVs</li> <li>• Specific parking area required for swapping</li> <li>• In comparison to SCR (Table 1), larger space requirements for battery swapping station</li> <li>• In comparison to SCR (Table 1), more conspicuous battery swapping station and battery swap process</li> <li>• In comparison to SCR (Table 1), SCU (Table 2), SCP (Table 3) and SCW (Table 4), more complex charging infrastructure</li> </ul>
<i>Operation</i>	<ul style="list-style-type: none"> <li>• Not limited to electric HDVs</li> <li>• In comparison to SCR (Table 1), SCU (Table 2), SCP (Table 3) and SCW (Table 4), shorter vehicle downtime</li> <li>• In comparison to SCR (Table 1), SCU (Table 2), SCP (Table 3) and SCW (Table 4), less susceptible to accidental damage and misuse</li> </ul>	<ul style="list-style-type: none"> <li>• Maintenance and repair expenses of moving and connecting parts</li> </ul>
<i>Technological readiness and standardization</i>	<ul style="list-style-type: none"> <li>• Charging technology specifically designed for automation</li> <li>• Existing standards for battery swapping</li> <li>• Commercialized</li> </ul>	<ul style="list-style-type: none"> <li>• Not based on widespread and standardized charging technology</li> </ul>
<i>Miscellaneous</i>	<ul style="list-style-type: none"> <li>• Battery swapping decoupled from battery charging, well suited for V2G approaches</li> <li>• Possibility for choice of re-installed battery</li> </ul>	<ul style="list-style-type: none"> <li>• Need for standardized, robust batteries</li> <li>• Need for standardized charging stations</li> <li>• More batteries than BEVs necessary</li> <li>• Leasing model for batteries required</li> </ul>

With advantages and potentials come challenges. First, there is a need for standardized batteries. The standardization extends to the batteries' physical dimensions, mounting and dismounting procedures and electrical connections to the vehicle. The batteries' capacities,

voltages, powers and management systems must not necessarily be standardized [94]. However, they must be compatible with different vehicle systems [19]. The standardization of the batteries limits the innovative power and the flexibility of both the vehicle and the battery manufacturer, and the uniqueness and the design of the products [19,97]. Besides being standardized, the batteries must be robust, as they have to withstand frequent removals and installations [19]. In addition to the standards for the batteries, there is a need for standards for the charging stations regarding, e.g., their equipment [94]. Certified equipment, which determines whether the battery satisfies minimum standards and can therefore be installed in the vehicle, is crucial for consumer acceptance, as most consumers might raise concerns regarding the battery's SOH and its safety [93,94]. Batteries that do not satisfy minimum standards are selected for second life or recycling purposes [94]. Third, there is a need for an additional and standardized BSS–battery–vehicle interface in the shape of a battery-contacting system and an interlocking system [98]. A fourth challenge is that, in comparison to the other static charging infrastructures, the BSS is larger, more conspicuous and more complex, as it requires swapping, storage and charging systems to handle the batteries [19,92]. To reduce the large space requirements, the BSS can be built upward [13]. A fifth challenge lies in the battery swap technology requiring more batteries than BEVs, which results in additional costs, resource consumption and emissions. A sixth challenge is developing a leasing model for the batteries [19]. In contrast to other static charging technologies, battery swap technology can not be scaled up entirely in parallel to the scale-up of BEVs. Finally, a specific parking area is required for charging, the moving and connecting parts of the BSS result in maintenance and repair expenses, and the battery swap technology is not based on a widespread and standardized charging technology.

Examples of battery swap technologies are introduced below.

- **SANY:** In 2022, the company put its first intelligent BSS into operation. This BSS requires 50 m<sup>2</sup> of space, can be installed within one day, stores eight batteries, charges a battery in one hour and can perform 168 battery swaps per day. The BSS serves SANY's HDTs, dump trucks, concrete mixer trucks and truck loaders. The battery swapping process begins with an electric HDV docking at the BSS and the driver scanning a QR Code. If authenticated, the vehicle is unlocked, the battery is swapped and the vehicle is locked again. With the help of an assistance vehicle, the process is completed within five minutes [99]. In 2022, the companies SANY and CATL announced a project to demonstrate the battery swap technology for electric HDTs and dump trucks in Fujian province, China [100].
- **Geely:** This company offers a battery swap technology for cement mixers and semi-trailer trucks. The batteries of these vehicles are located behind the passenger cabins and can be accessed from the top. A crane positioned above the vehicle in the BSS drops down, lifts the battery up and transports it to the storage area, where a charged battery is waiting. The entire swapping process takes five minutes. Similarly to the BSS developed by SANY, the driver is authenticated using a QR Code; the BSS can store eight batteries and the batteries can be charged in one hour. Geely's BSS requires 19 m<sup>2</sup> of space, is equipped with solar panels and can serve up to 50 vehicles [101].
- **Janus Electric:** Janus Electric is an Australian company that fits existing HDVs with its battery swap technology. Once installed, the batteries can be swapped at BSSs within four minutes. The BSSs are powered by renewable energies and enable a bidirectional energy transfer [102]. Following the presentation of the first prototype in 2021 and a 12-month trial involving five prototypes, the battery swap technology is currently commercially available in Australia [102,103].
- **Project eHaul:** The project's primary aim is to develop and implement an automated BSS for electric HDVs. This BSS, which is the first of its kind in Germany, will be tested by two semi-trailer trucks for several months. Besides the BSS, a business model will be designed [104]. In April 2023, the electric trucks were put into operation. In October 2023, the build-up of the BSS was completed (see Figure 7). Once all the components are synchronized, the testing will begin [105].



**Figure 7.** BSS designed within the framework of the eHaul Project (reproduced with permission from Forschungsverbund “eHaul”).

Similarly to the static wireless charging technology, the TRL of the battery swap technology differs greatly. For example, in November 2023, Europe’s first automated BSS for electric HDVs was opened in Germany [106]. As testing under experimental conditions is currently in progress, a TRL 4–5 is proposed. These TRLs mark the transition from the technology being validated in a lab to the technology being validated in a relevant environment. In contrast, the battery swap technology offered by the Janus Electric company is commercially available in Australia indicating a TRL up to 9 [102]. In China, 49.5% of the 36,000 electric HDTs sold in 2022 are swap capable, which also implies a TRL up to 9 [107]. However, this technology may also still be developed further to address potential challenges.

## 2.2. Dynamic Charging Technologies

### 2.2.1. Dynamic Conductive Charging via Overhead Contact Line

Next, dynamic charging technologies are investigated, beginning with conductive charging technology using an overhead contact line.

Charging via an overhead contact line requires three main components:

1. The rectifier substations;
2. The contact line;
3. The pantograph.

The rectifier substations supply energy to the contact line [108]. Therefore, they rectify and transform the high or medium voltage AC provided by the grid into the low voltage DC required by the batteries [12,109]. The final voltage levels usually range from 600 to 750 V. The substations are placed every 1–10 km alongside the road and typically provide 2–4 MW of power per substation [110]. The exact positions, powers and the total number of stations depend on the route and the number of charging vehicles [12,110]. Besides the rectifier and the transformer, a substation contains switches, control systems and an inverter to operate the charging system and to feed the recuperated energy into the grid [12,108]. In contrast to train systems, the charging system for electric HDVs requires a two-pole overhead contact line. The reason for this is that the current cannot be returned via rails [12]. The positive and the negative pole are realized as two contact wires included in two separate catenary systems. Next to the contact wires, which at a height of around 5.1 m run parallel to the road, each catenary system consists of a messenger cable and droppers. The catenary systems are held by brackets and add-on parts attached to masts, and each cover 1.5 km of road. The masts are placed every 60 m [108]. The overhead contact line of the eHighway in Schleswig-Holstein, Germany, is depicted in Figure 8. To charge a vehicle via an overhead contact line, a pantograph must be installed on the roof [97]. As soon as the vehicle is



located below the contact line, the arm of the pantograph extends and connects four carbon contact strips to the two contact wires [111] (see Figure 8). If the supplied energy exceeds the energy required to propel the vehicle, a battery can be charged. This battery can then power the vehicle on non-electrified road sections [97]. It is important to notice that the power supplied to the vehicle is used to propel the vehicle and to charge the battery [112]. Besides the three main components, safety measures, such as restraint systems located alongside the road, are necessary [108].

The charging of buses via overhead contact lines (trolley buses) was introduced in the 20th century. However, due to the vehicles' inflexibility regarding the route, the use was limited. In the last decade, trolley buses equipped with batteries were developed and tested. Generally, the charging system for trolley buses resembles that for electric HDTs [113].

The advantages, the potentials and the challenges of dynamic charging technology using an overhead contact line are summarized in Table 6.

The first advantage of charging technology using an overhead contact line is that it is based on the widespread and standardized trolley systems for trains, trams and trolley buses [108]. The second advantage is that the charging does not require any downtime, which results in fewer vehicles and fewer drivers having to be deployed [114]. Additionally, the reduced downtime leads to dynamic charging technologies suiting automated vehicles best, as they do not require a driver-related break. With dynamic charging technologies charging while driving is possible. Consequently, the existing infrastructure, i.e., the roads, are used for charging and no specific parking area is required. This, however, results in the road and the charging system influencing each other, for example regarding maintenance [12]. It is not necessary to electrify the entire road. Gaps can be left, where a battery or an internal combustion engine propels the vehicle [109]. On the one hand, this reduces the infrastructure costs; on the other, it entails an increase in battery costs or greenhouse gas emissions [109,115]. Furthermore, as the vehicle is propelled by the electricity provided by the overhead contact line, the battery capacity can be reduced and thereby also the battery weight, space requirements and costs, the resource consumption and the grid connection power, while the payload can be increased [6,9,12]. This is possible, provided that the distance traveled on the non-electrified roads is limited [12]. If a large number of kilometers is electrified, the vehicles can have a high range without requiring large battery capacities, and the charging power and the local grid connection power can be reduced [6,12]. Additionally, frequent shallow charging with dynamic charging technologies is better than sporadic deep charging with static charging technologies regarding battery lifetime [116]. Another possibility lies in exploiting synergies with the static charging technology using a pantograph regarding, e.g., standardization [9,97]. Standards for dynamic charging technology using an overhead contact line are under development [110]. Dynamic charging technologies were specifically designed for automation. Finally, in comparison to static charging technology using a robot, dynamic charging technology using an overhead contact line is less susceptible to misuse. However, as the vehicles are moving, it is more susceptible to accidental damage. It also has larger space requirements and has a more conspicuous charging infrastructure and charging process. Dynamic charging technology using an overhead contact line requires additional vehicle components in the shape of a pantograph. Due to the minimum height of the contact wires and the restricted reach of the pantograph, the charging technology is limited to electric HDVs [108,109]. The extended pantograph results in increased air resistance and therefore also in increased energy costs [111,117]. As the charging technology is both conductive and dynamic, wear and tear is also increased. This results in higher maintenance and repair expenses in comparison to the static charging technologies. Further challenges are the possible negative effects of the charging infrastructure on the avifauna and the fact that the charging technology can require changes in the driving speed and distance and lane management [118]. Additionally, the authentication and payment process must be implemented while driving, the scale-up of the charging infrastructure cannot entirely occur in parallel to the scale-up of the BEVs and there is a need for a standardized charging interface [6]. An object of research is the charging



infrastructure's sensitivity to strong winds and gusts, as these can result in a deflection and a vibrational excitation of the catenary systems [119]. Finally, charging technology using an overhead contact line faces the challenge of high infrastructure costs ranging from EUR 0.4 to 1.1 million per kilometer. However, the charging technology is expected to become a cost-competitive option regarding costs per vehicle-kilometer once high-frequented roads are electrified [110].

**Table 6.** Summary of dynamic charging technology using an overhead contact line (DCO).

Category	Advantages and Potentials	Challenges
<i>Vehicle adaptations</i>		<ul style="list-style-type: none"> <li>• Additional pantograph necessary</li> </ul>
<i>Infrastructure</i>	<ul style="list-style-type: none"> <li>• No specific parking area required for charging</li> <li>• Charging infrastructure can be limited to road sections</li> </ul>	<ul style="list-style-type: none"> <li>• Limited possibility to scale up charging infrastructure in parallel to scale-up of BEVs</li> <li>• In comparison to SCR (Table 1), larger space requirements for charging infrastructure</li> <li>• In comparison to SCR (Table 1), more conspicuous charging infrastructure and charging process</li> </ul>
<i>Operation</i>	<ul style="list-style-type: none"> <li>• No vehicle downtime</li> <li>• Charging while driving possible</li> </ul>	<ul style="list-style-type: none"> <li>• Limited to electric HDVs</li> <li>• In comparison to SCR (Table 1), more susceptible to accidental damage and less susceptible to misuse</li> <li>• In comparison to SCR (Table 1), SCU (Table 2), SCP (Table 3), SCW (Table 4) and BS (Table 5), increased maintenance and repair expenses</li> <li>• Possible change in driving behavior required</li> <li>• In comparison to SCR (Table 1), SCU (Table 2), SCP (Table 3), SCW (Table 4) and BS (Table 5), increased air resistance while driving and charging</li> </ul>
<i>Technological readiness and standardization</i>	<ul style="list-style-type: none"> <li>• Charging technology specifically designed for automation</li> <li>• Based on widespread and standardized railway technology</li> <li>• Standards for charging via overhead contact line under development</li> </ul>	<ul style="list-style-type: none"> <li>• Not commercialized; prototypes undergoing testing</li> </ul>
<i>Miscellaneous</i>	<ul style="list-style-type: none"> <li>• Possible synergies with SCP (Table 3)</li> <li>• Possibility to both reduce battery capacity and increase electric range</li> </ul>	<ul style="list-style-type: none"> <li>• Need for standardized charging interface</li> <li>• Possible effects on avifauna</li> <li>• Potentially affected by strong winds and gusts</li> <li>• Necessary to implement authentication and payment while driving</li> </ul>



**Figure 8.** The dynamic charging technology using an overhead contact line employed by Project FESH in Germany (reproduced with permission from FuE-Zentrum FH Kiel GmbH).

In Germany, there are currently three pilot projects testing charging technology using an overhead contact line for electric HDTs (see Table 7). The projects employ a technology developed by Siemens. Part of this technology is a pantograph, which can connect to or disconnect from the overhead contact line up to driving speeds of 90 km/h and automatically disconnects in the case of the vehicle swerving or indicating [120].

**Table 7.** German pilot projects testing charging technology using an overhead contact line.

Pilot Project	FESH	eWayBW	ELISA
Location	Schleswig-Holstein	Baden-Württemberg	Hessen
Road Type	motorway	main road	motorway
Electrified Section	5 km per direction	3.95 km per direction	12 km north–south, 5 km south–north
Drive	Hybrid (ICE <sup>1</sup> )	Hybrid (ICE, FC <sup>2</sup> ), EV	Hybrid (ICE), EV
Number of Vehicles	5	9	11
Transport Type	Intermodal transport of goods	Shuttle service	-
End of Funding Period	2024	2024	2024/2025
Automated Operation	No	Yes	Yes
Sources	[111,121]	[122–127]	[128–130]

<sup>1</sup> Internal combustion engine. <sup>2</sup> Fuel cell.

Regarding trolley buses, there are at least 277 trolley bus systems operating worldwide [113]. Vehicle manufacturers offering trolley buses are Solaris, Hess and Iveco [131–133].

To determine the TRL for the dynamic charging technology using an overhead contact line for electric HDTs, the comparatively high number of research and demonstration projects employing the same technology, the already elapsed parts of the project durations, the many involved transport companies, the use of the operational environments and the ongoing testing has to be taken into account [12,97]. This indicates a TRL 7.

For the sake of completeness, a TRL is also assigned to trolley buses. Trolley buses are offered by the manufacturers Solaris, Hess and Iveco and therefore exhibit a TRL up to 9 [131–133]. This charging technology is also still undergoing development to address potential challenges.

### 2.2.2. Dynamic Conductive Charging via Contact Rails

The second option to charge a vehicle both dynamically and conductively is contact rails. Contact rails are placed in the road pavement and are accessible via a movable contact arm attached to the vehicle's underbody [109]. The charging system's build-up is similar to that using an overhead contact line, as it also requires rectifier substations. The substations are placed every 1–2 km alongside the road [112,134]. In addition, cables to supply the contact rails with energy and switching cabinets including sensors to detect the vehicles and energize the respective sections of the rails are installed. Generally, there are three types of contact rails:

1. Two parallel flush-mounted contact rails.
2. Two parallel embedded contact rails.
3. One segmented flush-mounted contact rail.

Each type of contact rail has its advantages and challenges. If the contact rails are flush-mounted, the contact arm can effortlessly establish a connection. However, as humans, animals and other vehicles can easily come in contact with the rails, additional safety-related efforts are required. If the contact rails are embedded, the safety of the road users is increased. In this case, though, the process of connecting the contact arm with the contact rails is more difficult, and dirt and wear debris can accumulate within the rails. Additionally, the embedded rails might represent a safety hazard for (motor-)cyclists. A single segmented flush-mounted contact rail offers the advantage that only the rail segment located below the vehicle is energized. Therefore, the safety is increased. However, an exact energizing of the contact rails, which also takes the vehicle length and vehicle speed into account, is required. This necessitates a reliable communication system. The different types of contact rails are incompatible. In contrast to charging technology using an overhead contact line, the contact arm is realized as a pick-up shoe [112].

Table 8 summarizes the advantages, the potentials and the challenges of charging technology using contact rails.

Charging technology using contact rails shares many of its advantages and potentials with charging technology using an overhead contact line. For instance, charging while driving is possible, the existing infrastructure, i.e., the road, is used, it is not necessary to electrify the entire road, there is the possibility to reduce the battery capacity and still ensure a high electric range, and there is no charging-related downtime required. Technology-specific advantages are that the contact rails are accessible to all vehicle types and that, in comparison to charging technology using an overhead contact line, the charging occurs unseen underneath the vehicle, resulting in a less conspicuous charging process and charging infrastructure [134]. Additionally, charging technology using contact rails requires less space than that using an overhead contact line. Further advantages and potentials are that the charging technology can draw on the experience of railway traffic with contact rails, that the charging technology was specifically designed for automation and that a standard for the dynamic charging via contact rails exists, namely CLC/TS 50717 [135]. Finally, there is the possibility to exploit synergies with static charging technology using an underbody coupler [51]. In comparison to charging technology using an overhead contact line, charging technology employing contact rails is less susceptible to accidental damage, but, due to the system layout, more susceptible to misuse. Considering the static charging technologies, charging technology using contact rails necessitates increased maintenance and repair expenses, and results in higher energy costs. Furthermore, vehicle adaptations in the shape of a contact arm are necessary, there is a need for a standardized charging interface and a need to implement the authentication and payment process while driving. Similarly to charging technology using an overhead contact line, a change in driving behavior regarding distance and lane management might be required. The infrastructure costs of charging technology using contact rails exceed those of charging technology using an overhead contact line [136]. Finally, there is only a limited possibility of scaling up the

charging infrastructure in parallel to the scale-up of BEVs, as, aside from the length of the electrified section, there is no room for maneuver.

**Table 8.** Summary of dynamic charging technology using contact rails (DCC).

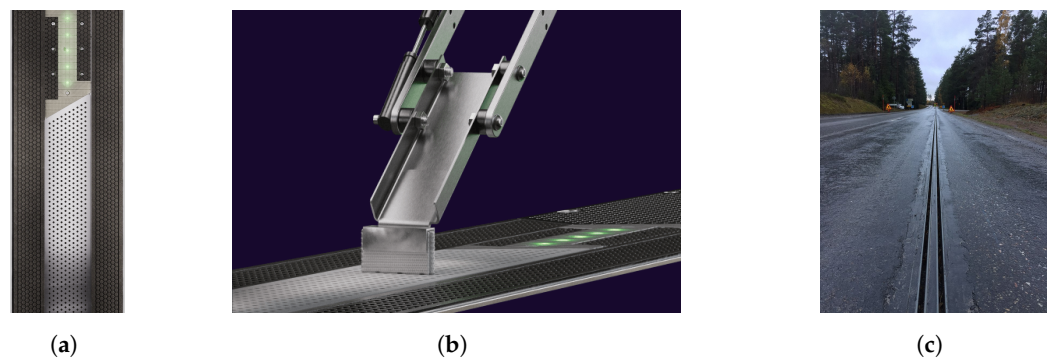
Category	Advantages and Potentials	Challenges
<i>Vehicle adaptations</i>		<ul style="list-style-type: none"> <li>• Additional contact arm necessary</li> </ul>
<i>Infrastructure</i>	<ul style="list-style-type: none"> <li>• No specific parking area required for charging</li> <li>• In comparison to DCO (Table 6), less space requirements for charging infrastructure</li> <li>• In comparison to DCO (Table 6), less conspicuous charging infrastructure and charging process</li> <li>• Charging infrastructure can be limited to road sections</li> </ul>	<ul style="list-style-type: none"> <li>• Limited possibility to scale up charging infrastructure in parallel to scale-up of BEVs</li> </ul>
<i>Operation</i>	<ul style="list-style-type: none"> <li>• Not limited to electric HDVs</li> <li>• No vehicle downtime</li> <li>• Charging while driving possible</li> </ul>	<ul style="list-style-type: none"> <li>• In comparison to DCO (Table 6), less susceptible to accidental damage and more susceptible to misuse</li> <li>• In comparison to SCR (Table 1), SCU (Table 2), SCP (Table 3), SCW (Table 4) and BS (Table 5), increased maintenance and repair expenses</li> <li>• Possible change in driving behavior required</li> <li>• In comparison to SCR (Table 1), SCU (Table 2), SCP (Table 3), SCW (Table 4) and BS (Table 5), increased air resistance while driving and charging</li> </ul>
<i>Technological readiness and standardization</i>	<ul style="list-style-type: none"> <li>• Charging technology specifically designed for automation</li> <li>• Build on experience of railway traffic with contact rails</li> <li>• Existing standard for charging via contact rails</li> </ul>	<ul style="list-style-type: none"> <li>• Not commercialized; prototypes undergoing testing</li> </ul>
<i>Miscellaneous</i>	<ul style="list-style-type: none"> <li>• Possible synergies with SCU (Table 2)</li> <li>• Possibility to both reduce battery capacity and increase electric range</li> </ul>	<ul style="list-style-type: none"> <li>• Need for standardized charging interface</li> <li>• Necessary to implement authentication and payment while driving</li> </ul>

Two companies located in Sweden offer charging technologies using contact rails.

- **Elonroad:** The contact rail developed by the company Elonroad can be used for both static and dynamic charging of various vehicle types [51,134]. The rail designed for dynamic charging is 9.2 m long, weighs 250 kg, supplies a charging power of up to 300 kW and enables a driving speed of up to 160 km/h. As the charging system is designed as a single flush-mounted contact rail, the polarity of the rail segments must alternate for the rail to be energized. Between each negative segment, there is a segment that can be both positive and negative. The substations energize these segments once an authenticated vehicle is detected above. According to Elonroad,

the charging system can transfer energy with an efficiency of up to 97%. Only vehicles equipped with a specific current collector can charge from the contact rails. The size of the current collector equals that of an A-segment passenger car, a city car. Besides the current collector, an onboard charger is required [134]. Since 2019, Elonroad has been demonstrating and testing its dynamic charging technology by charging, inter alia, an electric bus on a public road in Lund, Sweden. This project is scheduled to end in 2024 [137]. Additionally, the Aisin company has chosen to install Elonroad's dynamic charging technology at their 1 km test track in Mons, Belgium, to explore the electrified road systems and to develop their onboard charging equipment. The test track will be installed in 2024 [138]. The contact rail and current collector designed by Elonroad can be seen in Figure 9.

- **Elways:** The charging system developed by the company Elways consists of a contact rail embedded in the road pavement (see Figure 9). By placing the rail in a trench, energizing only sections of the rail, linking the current supply to a minimum driving speed and installing a turn-off device, Elways ensures the safety of its technology. To detect road obstacles, Elways employs radar. The water and the snow that accumulate in the trench are ploughed by either the contact arms or a special vehicle, and the ice is melted by a heating system [139]. Since 2018, Elways has been testing its charging technology using an electric 18 t truck and a road near Arlanda Airport, Sweden. The truck was charged with 200 kW of power at a driving speed of 60 km/h [140].



**Figure 9.** Dynamic charging technologies using contact rails developed by (a) Elonroad (contact rail) (reproduced with permission from Elonroad AB); (b) Elonroad (current collector) (reproduced with permission from Elonroad AB); (c) Elways (contact rail) (reproduced with permission from Elways AB).

As dynamic charging technology using contact rails is currently being demonstrated within the scope of two projects, which have been carried out for several years, partly incorporate transport companies and represent the first projects of their kind, a TRL 6–7 is suggested, indicating that the system is demonstrated in relevant and operational environments [137,140].

### 2.2.3. Dynamic Wireless Charging

Similarly to static wireless charging technology, dynamic wireless charging technology employs the magnetic resonance coupling technique. There are, however, differences in the build-ups of the charging technologies. The first difference lies in the layout of the primary coils. Dynamic wireless charging technology can encompass either one long primary coil or a multitude of small, aligned primary coils. The single primary coil is 10–100 m long and can charge several vehicles at once. The aligned primary coils are as large as the secondary coils and are connected either in series or in parallel. When using a single primary coil, only one primary coil and one primary station, including a rectifier, a high-frequency inverter and a compensation network, are required. This charging system is easy to control, enables constant mutual induction, and features a simple configuration and compensation network [77]. A single primary coil faces the challenges of high losses and high safety



risks, as the coil is permanently energized [15,77]. Furthermore, the maintenance and repair expenses are high and the coupling coefficient and therefore also the efficiency are low. When employing many aligned primary coils, only the primary coil closest to the secondary coil is energized, which results in reduced losses and greater safety. Also, the length of the charging track is more flexible. This system layout requires many primary coils, compensation networks and, depending on the design, high-frequency inverters, resulting in high material costs and a high system complexity. Additionally, to eliminate self-coupling, the primary coils are separated by great distances, which leads to mutual inductance and therefore the charging power varying with the position of the secondary coil [77]. The second difference is that the secondary coil of dynamic wireless charging technology is mobile. In the case of the aligned primary coils, only the primary coil closest to the secondary coil is energized. Therefore, the mutual inductance is monitored, as it indicates the distance between the coils. The third difference concerns the compensation networks, which, as parts of dynamic wireless charging technology, encompass both capacitors and coils. This increases the stability and the tolerance of misalignment, and enables a bidirectional energy flow and the charging of multiple vehicles simultaneously by one primary coil [18].

Besides requiring a communication system, dynamic wireless charging technology necessitates a foreign object detection system, a living object protection system and a driver assistance system to guide the vehicle while charging [9,11,15]. Furthermore, the EMC regarding other electrical systems and the environment must be ensured [9]. To do so, active or reactive resonant shielding can be employed. Active shielding defines the energizing of external coils to generate a magnetic field opposing that of the primary coil. Reactive resonant shielding extends active shielding by adding reactive components, which are excited by the primary coil's magnetic field [18].

Next to the influencing factors mentioned in Section 2.1.4, the charging power depends on the driving speed, the number of secondary coils energized by the same primary coil, the power quality and the total number of primary and secondary coils [14,141]. There is the possibility to place the secondary coils in the wheels of the vehicle to reduce the distance between the coils and increase the efficiency [10]. Furthermore, magnetizable concrete can be installed to direct and confine the magnetic field and thereby increase the efficiency [77].

A summary of the advantages, the potentials and the challenges of the dynamic wireless charging technology is given in Table 9).

Dynamic wireless charging technology shares many advantages and potentials with dynamic conductive charging technologies. For example, charging while driving is possible, the existing infrastructure, i.e., the road, is used, it is not necessary to electrify the entire road, there is the possibility of reducing the battery capacity and still ensuring a high electric range and there is no charging-related downtime required. Technology-specific advantages and potentials are the standards, which are currently under development, e.g., IEC PAS 61980-5 ED1 [142], the fact that the charging technology can draw on the experience and the standards of the static wireless charging technology and the possible synergies with static wireless charging technology by employing the same vehicle unit for example [77]. In comparison to dynamic charging technology using an overhead contact line, dynamic wireless charging technology requires less space and has a less conspicuous charging infrastructure and charging process. Additionally, as no vehicle components are extended while driving, the air resistance and therefore also the energy costs are reduced. Moreover, due to the fact that there is no physical connection between the vehicle and the infrastructure, there is less wear and tear and therefore less maintenance and repair work. Further advantages and potentials are that dynamic wireless charging technology is not limited to electric HDVs and that it is specifically designed for automation.

**Table 9.** Summary of dynamic wireless charging technology (DCW).

Category	Advantages and Potentials	Challenges
<i>Vehicle adaptations</i>		<ul style="list-style-type: none"> <li>• Additional vehicle unit necessary</li> </ul>
<i>Infrastructure</i>	<ul style="list-style-type: none"> <li>• No specific parking area required for charging</li> <li>• In comparison to DCO (Table 6), less space requirement for charging infrastructure</li> <li>• In comparison to DCO (Table 6), less conspicuous charging infrastructure and charging process</li> <li>• Charging infrastructure can be limited to road sections</li> </ul>	<ul style="list-style-type: none"> <li>• Limited possibility to scale up charging infrastructure in parallel to scale-up of BEVs</li> </ul>
<i>Operation</i>	<ul style="list-style-type: none"> <li>• Not limited to electric HDVs</li> <li>• No vehicle downtime</li> <li>• Charging while driving possible</li> <li>• In comparison to DCO (Table 6) and DCC (Table 8), less maintenance and repair expenses</li> <li>• In comparison to DCO (Table 6) and DCC (Table 8), no increased air resistance</li> </ul>	<ul style="list-style-type: none"> <li>• In comparison to DCO (Table 6), less susceptible to accidental damage and more susceptible to misuse</li> <li>• Possible change in driving behavior required</li> <li>• Efficiency depends on horizontal misalignment and vertical distance between coils</li> <li>• Tolerance to horizontal misalignment required</li> </ul>
<i>Technological readiness and standardization</i>	<ul style="list-style-type: none"> <li>• Charging technology specifically designed for automation</li> <li>• Based on standardized static wireless charging technology</li> <li>• Standards for dynamic wireless charging under development</li> </ul>	<ul style="list-style-type: none"> <li>• Not commercialized; prototypes undergoing testing</li> </ul>
<i>Miscellaneous</i>	<ul style="list-style-type: none"> <li>• Possible synergies with SCW (Table 4)</li> <li>• Possibility to both reduce battery capacity and increase electric range</li> </ul>	<ul style="list-style-type: none"> <li>• Need for standardized charging interface</li> <li>• Necessary to implement authentication and payment while driving</li> <li>• Achievable charging power still unclear</li> </ul>

Dynamic wireless charging technology also shares many of its challenges with dynamic conductive charging technologies. For example, vehicle adaptations in the shape of a vehicle unit are required, there is a limited possibility to scale up the charging infrastructure in parallel to the scale-up of BEVs, a change in driving behavior, e.g., reduced speed, increased gaps and a ban on passing, might be required, and there is a need for a standardized charging interface and a mobile authentication and payment procedure [14]. In comparison to dynamic charging technology using an overhead contact line, dynamic wireless charging technology is less susceptible to accidental damage but, due to the system layout, more susceptible to misuse. Further technology-specific challenges are the sensitivity of the ground units to movements of the road surface, operating the charging system at the recommended frequency, as current systems work with lower frequencies, isolating the ground units so that the failure of a ground unit does not lead to the failure of the system, and the sensitivity of the system efficiency to the horizontal and vertical misalignment of

the coils [14,77]. The efficiency of dynamic wireless charging technology is more vulnerable to misalignment than the efficiency of static wireless charging technology. Therefore, the tolerance to horizontal displacement is considered more important in dynamic wireless charging systems and represents a challenge to be overcome [143]. The infrastructure costs of dynamic wireless charging technology exceed those of the dynamic conductive charging technologies [136]. Finally, in comparison to the dynamic conductive charging technologies, the power capability of dynamic wireless charging technology is limited [112].

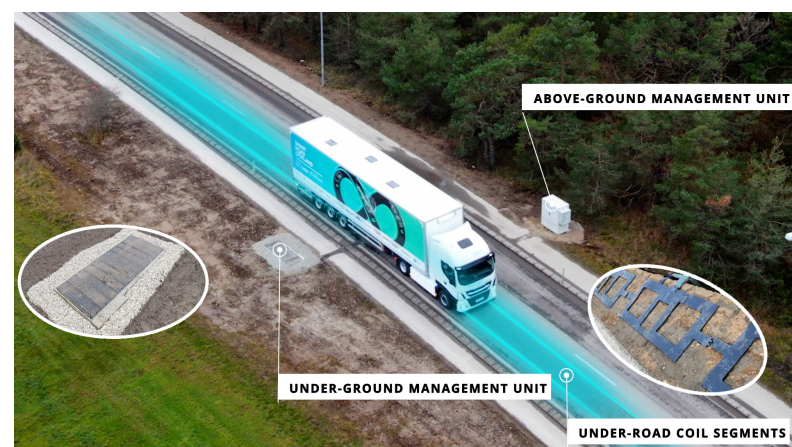
The Electreon company is developing a dynamic wireless charging technology for electric HDVs. This technology is being/will be demonstrated, explored and tested within the framework of various projects (see Figure 10 and Table 10).

Electreon's primary coils are embedded in the road pavement, are energized once an authenticated vehicle is located above and can be installed at a rate of 1.6 km of coils per night [144,145]. The corresponding primary stations can be installed underground, minimizing the space requirements and the technology's conspicuousness. The charging technology has a life time of 10 to 20 years, is not affected by snow or ice, and can be installed in tunnels if the energy supply is guaranteed [144]. In Visby, Sweden, an electric truck was charged with an average power of 100 kW while travelling at speeds of up to 80 km/h [146]. In 2023 and 2024, Electreon is planning to test its charging technology at driving speeds of 120 km/h [144]. Currently, Electreon is offering a Charging-as-a-Service business model in which the customers pay a monthly subscription fee [147].

**Table 10.** Projects to test the dynamic wireless charging technology developed by Electreon.

Location	Start <sup>1</sup>	Status	EV Type	Road Type	Road Length	Sources
Norway	2024	Planned	Bus	Public road	-	[148]
USA	2022	Complete	Truck	Test track	0.05 km	[149]
USA	2023	Ongoing	Bus, shuttle, truck	Public road	1.61 km	[150]
Israel	2021	Complete	Bus	Public road	0.7 km	[151]
China	2024	Planned	Bus, truck	Industrial park, public road, port	Tens of km	[152]
Germany	2023	Ongoing	Bus	Public road	1 km	[87]
Germany	2024	Planned	Bus, shuttle, truck, passenger vehicle	Motorway	1 km	[153]
Germany	2021	Ongoing	Bus, passenger vehicle, van	Private roads, public roads	0.6 km	[154]
Italy	2021	Ongoing	Bus, passenger vehicle	Test track	1.05 km	[155]
Sweden	2021	Complete	Bus, truck	Public road	1.65 km	[146]
France	2024	Planned	Bus, truck	Motorway	2 km	[156]

<sup>1</sup> Start of Operation.



**Figure 10.** Layout of the dynamic wireless charging system designed by Electreon and installed in Sweden (reproduced with permission from Electreon Wireless Ltd.).

Another example is the dynamic wireless charging technology that is being developed by Purdue University and the Indiana Department of Transportation (INDOT). This technology enables dynamic charging of both passenger vehicles and HDTs up to speeds of around 100 km/h. The vehicles are equipped with a single receiver coil assembly and can be charged while driving on asphalt or concrete pavement. The technology has already been tested in the lab. Currently, the construction of a test site on a highway in Indiana, USA, is underway. The testing there will presumably begin in 2025 [157].

To determine the TRL of dynamic wireless charging technology, the projects employing the charging system designed by Electreon are examined. The primary aim of the completed and ongoing projects is to validate and demonstrate the charging technology and to display its benefits and feasibility on public roads with different vehicle types and in various use cases [87,146,149–151,154]. As a few of the projects already incorporate transport companies, a TRL 5–6 is proposed, indicating that the technology has been validated and demonstrated in a relevant environment [146,151,154]. As the charging technology that is being developed by Purdue University and the INDOT has been tested in the lab and will be tested in its relevant environment starting 2025, a TRL 4 is assigned [157].

### 3. Discussion and Conclusions

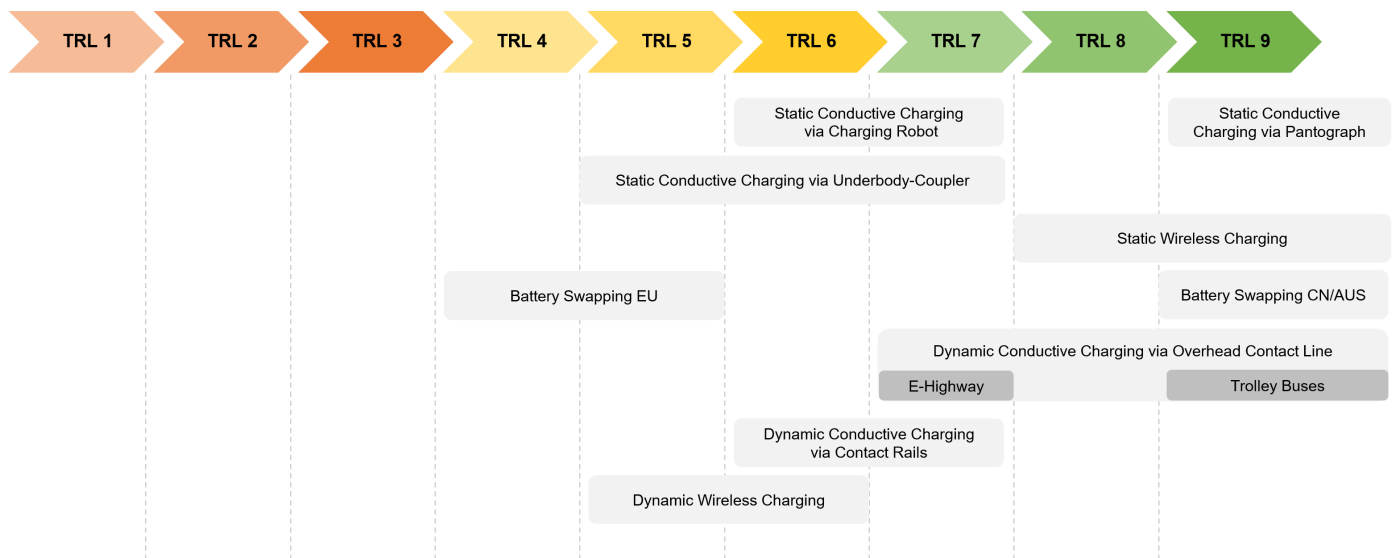
The in-depth analysis of the automated charging technologies for electric HDVs reveals a dynamic landscape of innovation and development. In the realm of the static conductive charging technologies, charging robots, underbody couplers and pantographs are evolving. Charging robots, which blend automation with traditional charging via a plug and a cable, are advancing towards higher TRLs, although challenges regarding adaptability and environmental resilience remain. Research in this domain is expected to focus on enhancing the robotic flexibility and durability. Underbody couplers, which offer a discreet charging solution, face the hurdle of standardization and compatibility across different vehicle models. Future research should concentrate on improving alignment mechanisms and establishing universal standards on which ideally all OEMs agree. Pantographs, which are the most mature of the static conductive charging technologies, continue to be refined for better integration with various vehicles and infrastructures. It may be prudent to establish standards that prescribe specific technologies, such as the top-down or the vehicle-side pantograph for certain use cases, such as urban delivery traffic. This would ensure interoperability and prevent the unnecessary proliferation of two sets of charging infrastructure. Static wireless charging technologies, while commercially deployed in some cases, confront obstacles regarding broader implementation and efficiency. It remains to be evaluated whether the minimal visual intrusiveness can outweigh the disadvantages in efficiency. Battery swapping, an innovative approach to reducing vehicle downtime, varies significantly in readiness. Some systems have reached commercial availability, while others are still in demonstration phases. The scalability of this technology is crucial, given its potential to revolutionize HDV operations by significantly cutting down on charging times.

Dynamic conductive charging using overhead contact lines and contact rails shows promise, particularly for high-traffic HDV routes. Overhead contact lines are more advanced, given that a comparable technology has been in use for decades in trolley buses and trains, whereas the contact rail approach is still in a demonstration phase. Dynamic wireless charging, despite its lower efficiency and higher costs, offers substantial benefits in flexibility and adaptability as well as the potential for invisible integration into the road, and low wear and tear.

All dynamic technologies and battery swapping are heavily reliant on political decisions at the national or, ideally, international level (e.g., within the EU) for rapid expansion, as they cannot be scaled in parallel with electric HDVs but must be deployed swiftly along all main routes for the technology to be successfully implemented. Should such decisions be deferred (e.g., in favour of static technologies), these technologies risk remaining niche solutions, suitable only for specific applications like mines with high transport demands. As these technologies evolve, integration into existing infrastructures, standardization and

addressing safety and environmental concerns remain significant challenges. The future of charging technologies for electric HDVs is likely to witness increased research and development in these areas, focusing on enhancing efficiency, reducing costs and ensuring seamless integration into transportation systems.

Figure 11 gives an overview of the TRLs of all analyzed technologies. It is evident that automated charging technologies for heavy-duty commercial vehicles are in the transition phase between testing in relevant environments and final market maturity. It is interesting to note that nearly half of the technologies studied have already reached market maturity in certain forms and are commercially available in certain places around the world.



**Figure 11.** Technology readiness level of automated charging technologies.

In conclusion, the landscape of automated charging technologies for electric HDVs is marked by a blend of innovation, challenges and vast potential. The continuous development of these technologies is an important task for realizing a sustainable, efficient and environmentally friendly transport sector.

**Author Contributions:** Conceptualization, E.L. and A.G.; methodology, E.P.; formal analysis, E.P.; investigation, E.P., A.G. and E.L.; resources, D.G. and E.L.; data curation, E.P., A.G. and E.L.; writing—original draft preparation, E.P.; writing—review and editing, D.G., E.L. and A.G.; visualization, E.L. and A.G.; supervision, D.G., E.L. and A.G.; project administration, D.G., E.L. and A.G.; funding acquisition, D.G. and E.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Federal Ministry of Education and Research of the Federal Republic of Germany as part of the Research Campus Mobility2Grid [[www.mobility2grid.de](http://www.mobility2grid.de) (accessed on 21 May 2024)], funding code: 03SF0674A.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** We wish to express our gratitude to the manufacturers of the charging technologies showcased in this study for granting us the permission to utilize their images and for their valuable contributions, insights and discussions pertinent to this work. We acknowledge support by the Open Access Publication Fund of TU Berlin.

**Conflicts of Interest:** The E.L. is employee of IVU Traffic Technologies AG. The paper reflects the views of the scientists, and not the company.



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