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Lead author	Seyed Mahdi Miraftabzadeh (POLIMI)				
Co-author(s)	Michela Longo (POLIMI), Morris Brenna (POLIMI), Frank Judell (AMINA), Fredrik Lima (AMINA), Tommaso Reschiglian (DTU), Zoltan Mark Pinter (DTU), Christian Thren (EASELINK), Samuel Matias (CNET), Diogo Vasconcelos (EEM), Cindy Lascano (INESC ID), Hugo Gabriel Valente Morais (INESC ID) and Sheikh Mostafa (INESC ID), Ville Naumanen (KEMPOWER)				
Peer reviewer(s)	Blaž Dobravec (EG), Teresa Schettino (ATM)				
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EXECUTIVE SUMMARY

This deliverable reviews the present capabilities and near-term evolution of conductive and wireless charging technologies that support passenger battery-electric vehicles (BEVs), heavy-duty trucks and buses, and electrically powered vessels. The study consolidates data on technical specifications, energy efficiencies, capital and operating costs, charging rates, and deployment maturity for four pillars of today's infrastructure, AC charging, DC fast charging, inductive wireless systems, and bidirectional (vehicle-to-grid) interfaces, drawing on manufacturers' data sheets, field measurements, and the most recent regulatory and market reports from Europe, North America, and East Asia. On this basis it establishes a performance baseline against which emerging solutions can be gauged.

The analysis shows that conventional single- and three-phase AC equipment remains the dominant option for home, workplace, and depot refuelling because of its low cost and compatibility with existing low-voltage networks, yet unmanaged clustering of 7–22 kW chargers can already overload distribution transformers in dense urban areas. DC fast-charging infrastructure, deployed chiefly along inter-urban corridors and in logistics hubs, is progressing rapidly from 50–350 kW cabinets toward megawatt-scale systems able to refuel heavy-duty trucks in minutes; however, such power levels raise new challenges in power-quality compliance, cooling, and grid-connection economics. Commercial wireless pads now reach 11 kW static charging with typical efficiencies of 90 % and are being tested for automatic taxi and shuttle services, while dynamic inductive concepts remain at the demonstrator stage. Bidirectional power transfer is moving from niche pilots to early market offerings as the ISO 15118-20 communication standard matures, opening a path for parked vehicles to provide frequency regulation and local back-up power, but scalable business models depend on clearer market-access rules and cybersecurity provisions.

Looking ahead, the report identifies five trends that are likely to shape the sector over the next decade. First, megawatt-class DC equipment for trucks, coaches, and short-sea vessels will become commercially viable as connector standards and high-voltage battery architectures converge. Second, smart-charging algorithms that combine price-based scheduling, grid-constraint signals, and behind-the-meter storage will shift charging loads away from peak periods and reduce network-upgrade costs by up to 40%. Third, fully automated conductive couplers and higher-efficiency wireless links will improve user convenience and enable unmanned depot operations. Fourth, multifunctional charging hubs that co-locate solar PV, stationary batteries, hydrogen electrolyzes, and retail services will emerge as local energy ecosystems. Finally, regulatory harmonization, covering connector geometry, cybersecurity,

roaming protocols, and dynamic tariffs, will be essential to unlock cross-border interoperability and centralize economies of scale.

By mapping both the state of the art and these forward-looking trajectories, Deliverable 2.1 pinpoints the technical bottlenecks and regulatory gaps that still hinder mass deployment, while highlighting the most promising opportunities for higher-power, interoperable, and grid-aware solutions. The findings feed directly into subsequent project tasks that will specify smart-charging architectures, develop grid-integration models, and outline investment priorities for accelerating Europe’s transition to zero-emission road and maritime transport.

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GLOSSARY OF TERMS AND ACRONYMS

Table 1 – List of acronyms

Acronym	Term
AC	Alternating Current
ACD	Automatic Connection Device
BEVs	Battery-Electric Vehicles
BESS	Battery Energy Storage Systems
BMS	Battery Management System
BPT	Bidirectional Power Transfer
CaaS	Charging-as-a-Service
CCCV	Constant Current Constant Voltage
CCS	Combined Charging System
CPCV	Constant Power Constant Voltage
DC	Direct Current
EVs	Electric Vehicles
EVSE	Electric Vehicle Supply Equipment
HDVs	Heavy-Duty Vehicles
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LCC	Inductor-Capacitor-Capacitor
MG	Morris Garages
MSCC	Multi-Stage Constant Current
OBC	Onboard Charger
OCPP	Open Charge Point Protocol
PV	Solar Photovoltaic
RES	Renewable Energy Sources
RIPT	Resonant Inductive Power Transfer
SAE	Society of Automotive Engineers
SS	Series-Series
TEN-T	Trans-European Transport Network
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home

Acronym	Term
V2L	Vehicle-to-Load
VGI	Vehicle-Grid Integration
WPT	Wireless Power Transfer

1. INTRODUCTION

Electrifying road, maritime, and heavy-duty transport has moved from vision to urgent mandate in the EU Green Deal and Repower EU plans [1], [2]. Yet the pace at which battery-electric vehicles (BEVs) and plug-in vessels can replace internal-combustion assets is now determined less by battery cost than by the maturity, interoperability, and grid impact of charging infrastructure. Deliverable D2.1 of the AHEAD project, Charging Technology Assessments, consolidates the latest technical, economic, and regulatory knowledge on conductive, inductive, bidirectional, and high-power charging solutions for light-duty EVs, heavy-duty trucks, buses, and vessels. By identifying the strengths and blind spots of each option, the report lays the technical foundation for AHEAD's wider goal: accelerating affordable, grid-friendly and user-centric electrification across Europe. This introductory chapter frames why charging matters, recounts the technological and policy landscape, and states the specific objectives and analytical boundaries of the present deliverable.

1.1. Background

Public charging infrastructure has grown at a spectacular but uneven pace. China already hosts more than two million public charge points, whereas the European Union, through the Alternative Fuels Infrastructure Regulation (AFIR) [3], stipulates that by 2026 member states must guarantee at least 1.3 kW of publicly accessible capacity for every registered electric passenger car and install high-power DC stations at 60-kilometre intervals along the core TEN-T corridors [4]. Deployment patterns, however, diverge sharply: the Netherlands has focused on dense urban AC grids, New Zealand boasts the world's highest ratio of fast to slow chargers, and the United States relies heavily on federally funded corridor fast-charging programs.

The technology mix behind those numbers is equally varied. Conventional AC charging—typically 3.7 kW to 22 kW—remains the workhorse for overnight and workplace refuelling because the equipment is inexpensive and the existing 230/400 V distribution network requires minimal upgrades, though neighbourhood clusters of 11 kW home chargers can still overload local transformers and push peak demand into the evening. To shorten dwell time, DC fast chargers bypass the vehicle's on-board converter and already deliver up to 400 kW, with the Megawatt Charging System standard scaling that figure to 3.75 MW for heavy-duty trucks and ferries. Innovations such as 800-V modular power stages, bidirectional topologies and battery-buffered cabinets promise efficiency gains but introduce additional cost and power-quality challenges, especially for legacy 400-V fleets. Meanwhile, wireless inductive pads and automated conductive robots are beginning to eliminate the plug-handling bottleneck for autonomous cars, logistics depots and quay-side vessels, though efficiency losses and mechanical robustness remain open questions.

Beyond simply refuelling, charging systems are becoming active assets for the wider energy system. Bidirectional interfaces turn parked electric vehicles into mobile batteries that can provide frequency regulation, peak shaving and emergency backup; large-scale demonstrations have already proven the concept in Japan through CHAdeMO, and ISO 15118-20 now extends similar functionality to CCS fleets in Europe [5]. This convergence of mobility and power regulation heightens concerns over cybersecurity, market access and fair remuneration, but it also unlocks substantial operating flexibility. Operators in the Netherlands, for instance, use dynamic load-management algorithms, on-site photovoltaics and behind-the-meter storage to serve up to six times more vehicles without reinforcing the grid, reducing upgrade costs by roughly 40% and increasing user satisfaction, evidence of the systemic value of coordinated, grid-integrated charging.

1.2. Objectives and Scope

Deliverable 2.1 aims to give a current and forward-looking overview of electric-vehicle charging technologies in clear, academic prose. It first examines the present “state of the art,” reviewing conventional AC chargers, today’s DC fast-charging networks, emerging inductive wireless systems, and vehicle-to-grid or other bidirectional setups that let stationary vehicles support the power grid. The discussion then turns to likely developments over the coming decade: very high-power DC equipment sized for heavy-duty trucks and vessels, smart-charging functions that align demand with grid conditions, fully automated or more efficient wireless interfaces, and integrated charging hubs that combine renewables, stationary storage, and fleet services. Throughout, the report identifies the main technical and regulatory obstacles to widespread deployment and shows how open standards, and consistent rules can accelerate the adoption of higher-power, interoperable, and grid-friendly solutions. In doing so, Deliverable 2.1 supplies the factual basis that later work packages will use when designing smart-charging architectures and integration strategies for Europe’s transition to zero-emission transport.

2. AC CHARGING

With more people switching to electric vehicles (EVs), reliable and efficient charging is essential. While fast DC charging gets a lot of attention, AC charging is still the most common method for everyday use. AC charging plays a foundational role in electric vehicle (EV) adoption, particularly within residential and public environments. In residential contexts, Level 2 AC chargers (typically 240V, 16–40A) are the standard for overnight charging, allowing most EVs to recover 10–60 km of range per hour depending on the power level and onboard charger capacity. This aligns well with average daily driving distances and user behaviour patterns. Public AC chargers, often installed at workplaces, commercial centres, and curbside locations, extend this charging model into urban and semi-urban mobility ecosystems. These installations typically operate at similar power levels but must support higher session turnover.

From an infrastructure planning perspective, the wide deployment of AC chargers presents both opportunities and challenges. On one hand, AC units are relatively low-cost, easier to install, and impose fewer site constraints than DC fast chargers, making them ideal for distributed deployment. On the other hand, scaling AC infrastructure requires dense coverage to ensure availability, especially in multifamily dwellings and dense urban areas, where private garages and dedicated circuits may be limited. Grid impacts are also non-negligible: though each AC unit has modest demand individually, the aggregate effect—especially when synchronized during peak residential load periods (e.g., 6–10 PM)—can introduce localized transformer overloading, phase imbalance, and voltage drop issues. Without managed charging or time-of-use incentives, widespread unmanaged residential AC charging could drive new peak demand curves, challenging traditional load forecasting and distribution planning.

The behavioural model encouraged by AC charging—frequent, long-duration, lower-power sessions—fundamentally shapes EV usage patterns and infrastructure demand. Understanding these dynamics is essential for utilities, grid operators, and urban planners aiming to optimize system performance, defer costly upgrades, and enable scalable, equitable electrification of transport. As such, this topic represents a core focus within the AHEAD project, where the interplay between user behaviour, charging infrastructure, and grid impact will be explored in detail. More in-depth analysis and technical considerations related to AC charging follow in later sections.

2.1. Charging Powers: 11 kW and 22 kW AC Charging

An 11 kW AC charging setup is commonly used at both home and public charging stations, requiring a three-phase power supply delivering 16 amps per phase on a 400V system. This level of charging power significantly shortens charging times when compared to standard 3.6 kW or 7.4 kW home chargers. For example, an electric vehicle (EV) equipped with a 60 kWh battery can be charged from 0 to 100% in approximately 5.5 hours using an 11 kW charger. In contrast, 22 kW AC charging, which is available at certain public stations and some high-end home installations, requires a three-phase power supply at 32 amps per phase. This higher power level can charge the same 60 kWh battery in about 3 hours. However, it's important to note that most EVs are limited to a maximum of 11 kW AC charging due to the capacity of their onboard chargers [6].

2.2. Charging Grid and Charging Power

Faster AC charging at power levels of 11 kW and 22 kW significantly reduces charging times, offering greater convenience for electric vehicle (EV) users. This is especially advantageous in regions like Europe, where three-phase power is widely available in commercial and industrial settings, supporting higher charging speeds. In particular, 22 kW AC chargers prove valuable for fleet operations and public charging environments, where rapid turnaround is crucial but installing costly DC fast charging infrastructure may not be feasible [6].

2.3. Household Power Availability

In most European households, standard electrical outlets provide single-phase power at 230V, which typically supports charging electric vehicles at power levels of 2.3 kW (10A), 3.6 kW (16A), or up to 7.4 kW (32A) if the circuit has been upgraded. In some regions, however, homes may have access to three-phase power, enabling higher charging capacities such as 11 kW (16A per phase) and, though less common in residential settings, 22 kW (32A per phase). Accessing these higher charging rates at home often requires upgrading the household electrical infrastructure and obtaining approval from the local utility provider, which may involve additional costs and coordination [7].

2.4. Onboard Charger (OBC) Capabilities

The onboard charger (OBC) plays a crucial role in electric vehicles by converting alternating current (AC) from the grid into direct current (DC) suitable for charging the battery. OBC power ratings vary depending on the vehicle. Single-phase OBCs, typically found in older or more affordable EVs, support charging levels between 3.6 kW and 7.4 kW. Most modern EVs are equipped with three-phase OBCs rated at 11 kW, which aligns with the capabilities of many public and home charging stations. A few select models, such as the Renault Zoe, feature 22 kW onboard chargers, allowing them to fully utilize the maximum output of 22 kW AC chargers. However, it’s important to note that the OBC sets the upper limit for AC charging speed—meaning that even if a public charger supplies 22 kW, an EV with an 11 kW OBC will still only charge at 11 kW [8].

3. DC FAST CHARGING

3.1. Introduction

Electric Vehicles (EVs) utilize various charging technologies, necessitating standardized levels to establish appropriate regulations. A modern plug-in EV comprises a battery, a Battery Management System (BMS), an electric motor, and an inverter for power transfer. Charging solutions are categorized as onboard and offboard chargers, and unidirectional and bidirectional chargers. This summary focuses on conductive charging methods. Conductive charging, the most common technique in commercial EVs, connects the EV battery to the power grid via cables. The International Electrotechnical Commission (IEC) provides a framework for defining various charging levels, contrasting with the Society of Automotive Engineers (SAE) standards prevalent in the USA. The IEC standards, specifically IEC-61851, regulate EV charging modes without imposing fixed power limits; actual power levels depend on local grid conditions and national electrical standards, leading to variability across regions[9]. The IEC outlines four charging modes:

1. **Mode 1:** Low charging application with an earthing system and circuit breaker, allowing limited communication between EVSE and EV. The current ranges from 8A to 16A, connecting with an AC grid at either 480V (three-phase) or 240V (single-phase), yielding a maximum output of 4kW (single-phase) or 13.3kW (three-phase). This mode is generally disallowed in the USA and isn't classified as a level in the SAE-J1772.
2. **Mode 2:** Offers moderate safety, suitable for home use with a regular power socket. It supports both single-phase (up to 8 kW) and three-phase (up to 15.3 kW) connections, allowing currents up to 32 A, featuring various protection mechanisms. In the SAE-J1772 standard, this mode aligns with Level 1, though it permits a maximum output of only 1.8 kW at 120 V for single-phase systems.
3. **Mode 3:** Establishes a connection through a dedicated EVSE outlet with built-in safety features and bidirectional communication. It accommodates higher power levels with current capacities up to 250 A, achieving a maximum output of 60 kW (single-phase) or 120 kW (three-phase). This mode corresponds to Level 2 in the SAE-J1772, providing faster charging at 208-240V and up to 19.6 kW.
4. **Mode 4:** Tailored for public DC fast charging stations, connects to the grid through a fixed system capable of delivering high power levels typically above 150 kW. This classification underscores the evolving landscape of EV charging, essential for ensuring efficient power delivery and safe operation across different regions.

3.2. Architecture

Historically, electric vehicle (EV) manufacturers have used 400V powertrains, leading to the widespread adoption of 400V DC fast charging infrastructure. However, the industry is now transitioning to 800V architectures due to several advantages, including reduced charging currents, lower system weight, and higher charging power.

A modular approach to charger design is the most efficient way to accommodate both 400V and 800V systems. Modular chargers leverage economies of scale and allow for dynamic voltage and current reconfiguration, making them adaptable to varying grid constraints and application needs. For example, these chargers can support multiple low-power chargers or fewer high-power chargers and switch between 800V and 400V charging modes.

The shift to 800V systems brings several technical and economic challenges. First and foremost is battery complexity. Doubling the system voltage requires twice the number of series-connected cells, which complicates battery management. This means more intricate balancing strategies and additional control layers to ensure safety and longevity.

Another critical issue is power electronics. The transition from 600V insulated-gate bipolar transistors (IGBTs) to 1200V versions introduces additional costs, as these higher-rated components are more expensive and may necessitate the redesign of power modules.

Lastly, compatibility with legacy infrastructure poses a challenge. Since most existing fast chargers operate at 400V, an 800V vehicle will require an onboard DC-DC converter to interface with these stations. While this ensures backward compatibility, the additional conversion stage introduces energy losses, reducing overall system efficiency [10].

3.2.1. AC vs. DC Connected Charging Stations

Charging stations can be connected to either AC or DC grids [11]:

1. AC-Connected Stations: More common due to existing metering and protection standards. However, they require individual AC-DC conversion stages for each charger, leading to higher costs and efficiency losses.
2. DC-Connected Stations: While they lack standardized metering and protection, they facilitate the direct integration of renewable energy sources (RES) and battery energy storage systems (BESS), improving power management and grid services.

3.2.2. Charging Infrastructure Configurations

1. Radial Configuration: All EV chargers, RES, and BESS connect to a single DC bus. A fault in the bus can disconnect all stations, but resilience can be improved by using two rectifiers to create independent DC buses.
2. Ring Configuration: Patented by ABB, this setup connects the DC bus through multiple paths to RES and BESS, ensuring fault isolation and service continuity. However, installation and operational costs are high.

3.2.3. DC Bus Polarity Architectures

1. Unipolar Architecture: All chargers connect to the same DC bus, making installation straightforward but vulnerable to faults. The choice of DC bus voltage is crucial, as future systems may need to support 400V, 800V, or even 1000V EVs.
2. Bipolar Architecture: Uses a neutral point to split the DC bus into three voltage levels (-Vdc, 0, +Vdc). This configuration enhances fault tolerance by allowing flexible connections for chargers, RES, and BESS. However, maintaining voltage balance in the DC link capacitors adds complexity and cost.

3.3. Topology

DC fast chargers (DCFCs) are essential for electric vehicle (EV) infrastructure, significantly speeding up charging times by delivering direct current (DC) power directly to the battery. Unlike AC chargers that rely on a vehicle's onboard converter, DCFCs can handle much higher power levels. They can be connected via AC or directly to DC sources, with options for unidirectional or bidirectional power flow, enabling vehicle-to-grid (V2G) and vehicle-to-home (V2H) applications.

Key components of DCFCs include an input filter for power stability, an AC-DC rectifier that converts AC to DC (utilizing various topologies), and a DC-DC converter that adjusts the voltage to the battery's needs. These converters can be isolated for safety or non-isolated for efficiency.

The evolution of DCFCs includes bidirectional capabilities and extreme fast charging (XFC) technologies, allowing for rapid charging comparable to gasoline refuelling, though this presents challenges like battery complexity and cost. Many charging stations are integrating battery energy storage systems (BESS) to optimize energy use and support grid stability. As EV adoption increases, ongoing research aims to improve efficiency, standardize protocols, and integrate renewable energy, enhancing the effectiveness of DC fast charging infrastructure [12].

4. WIRELESS CHARGING (INDUCTIVE)

4.1. WPT systems

Wireless Charging (WC) is one of the most interesting trends in mobility. WC enables the possibility of charging vehicles autonomously through Wireless Power Transfer (WPT). It also makes dynamic charging possible, breaking down the barrier of charging time waste during charging. There are two methods of WPT [13], [14]:

- Electromagnetic induction methods: also called near field applications, since they are the ones that can transmit power over shorter distances. Electromagnetic induction methods are:
    - Inductive Power Transfer (IPT).
    - Resonant Inductive Power Transfer (RIPT).
    - Capacitive Power Transfer (CPT).
- Electromagnetic radiation methods: also called far field applications, since they are the ones that can transmit power over longer distances. Electromagnetic radiation methods are:
    - Microwave Power Transfer (MPT).
    - Laser Power Transfer (LPT).

These technologies are the most studied for the implementation of WPT. Each of these technologies differs from the others not only in its operating principle, but also in characteristics depending on:

- Power range: the power the system can transmit.
- Operating frequency range: the operating frequency of the system.
- Operating distance range: the range of distances at which the system can operate.
- Efficiency: transmission efficiency.
- Electromagnetic Interference (EMI): presence of electromagnetic interference.
- Device size: size of transmitter, receiver and components required for power transmission.

- Safety: system security and any additional insulation or devices required.

In this context, Table 2 brings together the main technologies and features of the systems [13], [15].

Table 2 – WPT systems and reference quantities.

	IPT	RIPT	CPT	MPT	LPT
Power range	W ÷ hundreds of kW	W ÷ hundreds of kW	W ÷ few kW	Tens of kW	Expended MW
Operating frequency range	20 ÷ 200 kHz	1 kHz ÷ 38MHz	1kHz ÷ 20MHz	300 MHz ÷ 300 GHz	Higher than 1THz
Operating distance range	0 ÷ 50 cm	50 cm ÷ 5 m	Few mm ÷ tens cm	5 m ÷ tens of km	5 m ÷ tens of km
Efficiency	70 ÷ 98%	75 ÷ 98%	44.3% ÷ 93.4%	54%	Up to 45%
EMI	Low	Low	Low	Medium/moderate	Low
Size of devices	cm^3 ÷ m^3	cm^3÷ m^3	m^3	cm^3÷ m^3	cm^3÷ m^3
Safety	Safe	Foreign Object Detection (FOD) is required for high magnetic flux quantities	Electric field emission. Necessity of appropriated insulation	Damages living tissue	Damages living tissue

4.2. WPT technologies comparison

The electromagnetic induction (near field) and electromagnetic radiation (far field) methods represent two distinct approaches to WPT with their specific characteristics and applications. In the EV context, electromagnetic induction methods are generally preferable to electromagnetic radiation ones because of the efficiency, the transferable power, the safety and the practicality. Electromagnetic induction systems operate at a short range, from centimetres to meters, and transfer power through magnetic or electrical coupling, keeping the power transmission confined close to the source and receiver. This makes the system efficiency up to 90-95% under optimal conditions. In addition, electromagnetic induction systems are capable of transferring high powers, up to hundreds kW. Finally, short distance is not an issue in the EV context, as these are parked on or very close to WC stations. On the other hand, electromagnetic radiation methods transfer power over long distances, using electromagnetic waves such as microwaves or lasers. Although these systems can cover greater distances (tens of meters or more), they are less efficient due to the dispersion of power in the medium they pass through, and power dissipation can come from weather interferences. In addition, the transferable power is generally lower than that of electromagnetic induction systems, making them unsuitable for high-power applications such as charging EVs. Another critical aspect is safety: electromagnetic radiation systems can pose risks to human health and interfere with other devices due to the propagation of electromagnetic waves in the environment. In terms of cost and complexity, electromagnetic induction systems are more ready and used in applications such as WC of EVs. The technology is reliable, safe and interactable into existing infrastructures. In contrast, electromagnetic radiation systems require more complex components, such as antennas and alignment systems, and are still being developed for large-scale practical applications. In conclusion, electromagnetic induction methods are best suited to the EVs sector due to their high efficiency, ability to transfer high power, safety and adaptability to short distances. Electromagnetic radiation methods, although attractive for low-power or long-distance applications, are currently not practical for charging EVs, making electromagnetic radiation systems the preferred choice in this area [13], [14], [15].

IPT (and consequently RIPT) are part of the electromagnetic radiation group of systems with CPT. Both IPT and CPT have similar applications, including EVs. However, IPT is generally considered more suitable in this sector than CPT. IPT and RIPT is based on magnetic induction. Power is transferred via magnetically coupled from transmitter to receiver through magnetic fields. In contrast, CPT is based on capacitive coupling and power is transferred via electric (instead of magnetic) fields generated by electrostatically coupled capacitive plates, called electrodes. Due to the physical structure, such as the presence of a dielectric between the plates, and the use of high voltages to transfer similar powers to the corresponding inductive, in CPT losses are higher and efficiency is lower. As a result, for systems using inductive charging is easier to transfer power values from 1 up to 100 kW with respect to capacitive charging. CPT systems work with powers of up to a few kW mostly. In addition to the power limitation of CPT, there is also a distance limitation. CPT requires distances of few millimetres to maintain acceptable efficiency (>75%), which makes it less practical for automotive applications. It is also worth to mention that an efficiency of 75% is considered poor for an inductive system (IPT or RIPT). Furthermore, the safety aspect must be analysed for both systems. Inductive systems have in most applications a low magnetic flux density and are not dangerous to humans or animals. However, they can have interference with metal objects very close to the coils and between them. To mitigate this, FOD systems are studied and used. CPT systems, on the other hand, use electric fields, which can be more sensitive to external interferences and require more attention to avoid electrical discharges or safety risks. Subsequently, the costs of CPT systems are lower than IPT ones, since electrodes are cheaper than coils. On the other hand, maintenance costs can be higher in CPT, as CPT systems are more influenced by environmental conditions, while inductive systems have the coils in safe positions. The presence of moisture or dust can adversely affect the capacitive coupling and even damage the electrodes. Finally, CPT technology is less mature than inductive ones and will require further investments to reach the same technology readiness level. CPT systems are currently not suitable for EV charging due to limitations in terms of power and distance. It could find application in charging systems for low-power devices or in specific scenarios. However, some prototype applications in laboratories exist and are testing how to improve this technology. In conclusion, IPT and RIPT represent a more effective technology in the mobility sector at the moment than CPT. This is due to technical factors such as higher transferable power with coils and wider operating distances, but also to structural factors such as the adaptability of the systems to environmental conditions and their higher technology readiness level. CPT systems can be interesting for low power applications or in specific scenarios but currently struggle to meet the charging needs of EVs.

4.3. RIPT systems implementation

Considering the trade-off between the magnitudes involved, RIPT appears to be the technology of greatest interest to the mobility sector. The operating principle behind RIPT lies on Faraday’s law (the same of IPT) enhanced by resonance condition. Faraday’s law implies that an alternating current passes through a transmitting coil, it generates a variable magnetic field. If a second (receiving) coil is nearby, the variable magnetic field induces a voltage in the receiving coil, thus transferring energy without a physical connection (Figure 1) [16].

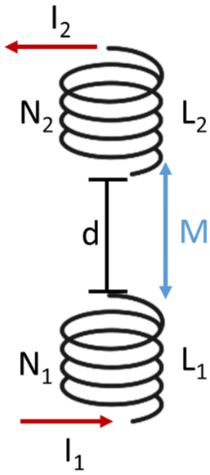

Figure 1 – IPT operating principle.

This physical principle can be represented mathematically through (1).

$$\varepsilon = -\frac{d\Phi_B}{dt} \quad (1)$$

Where, ε is the induced electromotive force, and $\frac{d\Phi_B}{dt}$ is the time derivative of the magnetic flux;

When two coils are magnetically coupled, the voltage induced in the secondary coil depends on the mutual inductance (M) between the two coils, which inductances are respectively L_1 and L_2 and they are connected by a coupling coefficient k (2).

$$M = k\sqrt{L_1 L_2} \quad (2)$$

The coupling coefficient k depends on the geometry of the coils, the distance between them and the alignment. A value of $k = 1$ indicates perfect coupling, while $k = 0$ indicates no coupling.

In addition to Faraday's law, RIPT combines electrical resonance. Both coils (transmitter and receiver) are tuned to the same resonance frequency (f_0), usually 85 kHz (3). This is done by adding a capacitor in series or parallel to each coil, creating a resonant LC circuit. Resonance maximises power transfer and reduces losses.

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

It is therefore useful to define two compensation sections of the RIPT system, one before the transmitter and one after the receiver. These compensation sections are composed of inductive or capacitive elements, depending on the characteristics required by the system. The two most common compensation topologies in the literature are the SS and the LCC [17]. The two topologies have different characteristics [18]. The SS compensation circuit has the following advantages:

- Simpler structure, due to the reduced magnetic component. This structure is easier to implement.
- The system keep an high efficiency at constant coupling coefficient.

However, SS topology has certain limitations such as:

- Poor adaptability to load variations and coupling.
- Higher harmonic distortion.
- Higher current at primary side, leading to higher Joule losses.
- Fixed structure, difficult power regulation through structural changes.

On the other hand, LCC compensation circuit, has different characteristics:

- Higher efficiency with variable load.
- L1c (compensation inductance) reduces current in primary commutation leading to high reliability.
- Improved compensation of coupling variations.
- Harmonics reduction, leading to a higher quality of transmission.

However, LCC topology has certain limitations such as:

- Circuit complexity, due to the introduction of additional components.
- Larger circuit and higher costs.
- Design complexity of the compensation components.

Those presented are not the only two topologies used by systems in the literature. It is also easy to find systems with hybrid topologies such as the LCC-S, which uses an LCC compensation circuit for the transmitter and an SS compensation circuit at the receiver, using a single capacitor connected in series. It is evident that, due to the circuit differences between the two topologies, the resonance conditions will not be the same. In the LCC compensation circuit they will inevitably be more complicated, due to the presence of more storage elements.

4.4. Wireless Charging Systems in Electric Mobility

Wireless charging applications in electric mobility are differentiated into two application clusters:

- Static applications, in which vehicles are stationary and positioned over a transmitter pad can recharge wirelessly.
- Dynamic applications, where vehicles are in motion and passing over a series of transmitter pads can recharge wirelessly.

The most common static applications are those involving autonomous vehicles, which through wireless charging do not need an operator to charge them through the plug. The operating principle of static wireless charging is simple. When the user parks the vehicle on top of a charging platform (charging pad), a corresponding device mounted on the underside of the vehicle detects the signal and starts charging the battery. The energy transmitted from the platform is collected by the vehicle's receiver coil and, via a power converter, is converted from AC to DC that can be stored in the battery. To ensure safety and efficiency, the system is equipped with a power control system and a Battery Management System (BMS), which communicate via a wireless network. Studies on this communication are directed towards Bluetooth technology, which works at much higher frequencies and avoids interference. Communication with the BMS makes it possible to constantly monitor the state of charge and intervene to prevent any risks, such as overheating or overloading. In addition, this system can tell when the system is working by initiating FOD systems to certify the absence of unwanted objects, or people, in the vicinity of the wireless transmission. These systems primarily serve to ensure the safety of the system by detecting the presence of living beings. There is a limit set by the ICNIRP standard, which requires that the magnetic flux that can be exerted in areas accessible to people does not exceed 27 μT precisely to protect their safety [19]. As with conductive charging, there are factors that affect the duration of the charging process such as:

- Source power level: The power output of the charging platform can vary widely. For light electric vehicles, it ranges from 3.7 kW up to 22 kW, while electric buses can reach power levels of around 200 kW.
- Size of the charging platform: The larger the platform, the greater the coupling area between the coils, improving the efficiency of energy transfer.
- Distance between coils (air-gap): The optimal distance between the transmitting coil (on the platform) and the receiving coil (on the vehicle) is generally between 150 and 300 mm for light vehicles. A greater distance reduces transfer efficiency.

Table 3 brings together the different applications of stationary charging, describing the characteristics of the charging system.

Table 3 – Suitable wireless charging locations and features for EV type.

Vehicle type	Location	Power range	Distance	Ref.
Passenger cars	Residential Parking; Commercial Areas; Public Areas	3.7 ÷ 22 kW	150 ÷ 300 mm	[20], [21]
Buses	Terminals; Depots	Up to 200 kW	200 ÷ 400 mm	[20], [22]
Heavy duty vehicles	Logistics centers; Depots	50 ÷ 300 kW	300 ÷ 500 mm	[21], [22]
Light duty vehicles	Logistic centers; Distribution centers; Company headquarters	7 ÷ 50 kW	150 ÷ 300 mm	[20], [23]
Bikes and scooters	Public spaces; Bike parking; Sharing mobility hubs	0.25 ÷ 1 kW	50 ÷ 150 mm	[24]

Stationary applications for mobility are manifold. This is related to several factors such as:

- Practicality of the solution, which removes physical connectors and cables.
- Safety and maintainability, as failures and damage are reduced since the coils are not accessible.

- Efficiency, as downtime in logistics centres is minimized.
- Scalability on different types of vehicles.

On the other hand, dynamic applications in mobility are more focused on range anxiety reduction, preventing the vehicle from unloading during motion. When an electric vehicle passes over a transmitter installed below the road surface, a receiver coil mounted on the vehicle picks up the magnetic field generated by the transmitter. The magnetic energy is then converted to DC via a power converter and managed by a battery management system (BMS) to charge the vehicle's battery pack, similar to the stationary case. For the dynamic charging system implementation, it is necessary to install transmitter plates and supply segments along predetermined routes, such as motorways or dedicated lanes. These supply segments can be organised in two main configurations:

- Centralized system, where a single large coil (5÷10 m) is buried in the street. This structure is simple but has higher losses and lower efficiency.
- Individual segment system, where several transmitters are installed in one segment of the route. Although infrastructure management is more complicated, the system is more efficient in transmission and has lower losses. Maintenance costs are also reduced as a single transmitter in the system can be replaced in the event of a failure.

Both systems are expensive to install and require major interventions to the existing infrastructure [25]. At the same time, when it comes to system efficiency, it must be remembered that power transfer depends on the alignment between the coils and the distance between the vehicle and the road. In the dynamic case it is more complicated to maintain optimal alignment. For passenger cars, the dynamic applications that are studied involve specific highway sections. The objective is to ensure that the EVs do not unload during the long motorway journey. On the other hand, for heavy vehicles or buses, predefined routes are designed for the vehicles to follow along which they can avoid unloading. Dynamic WC represents a significant breakthrough for the future of electric mobility, despite technical and economic challenges, as:

- Misalignment sensitivity, high output power variation can be caused by reduced misalignment.
- Limited range, since coupling factor is strongly affected by transmitter and receiver distance.

- Frequency stability, as in the case of SS configuration, that is fixed, and make it is easy to reduce coupling.
- EMI and electromagnetic safety require the presence of FOD systems. A magnetic flux limit is proposed by authorities (ICNIRP 27 μT rms).
- Coil design and size constraints are determined by a trade-off between larger size to improve transmission and smaller size to reduce weight and materials.
- Power handling and thermal management related to power leakage, which can create overheating.
- Costs and materials required are relevant since ferrites and coils are expensive. Moreover, the installation cost of transmitters is not negligible.
- Regulation is still under development and is evolving.

However, this technology has the potential to revolutionize the way electric vehicles are used, making them more practical and efficient. With the continued development of infrastructure and technology, the DWC could become a standard for sustainable transport.

5. VEHICLE-TO-GRID (V2G) AND BI-DIRECTIONAL CHARGING

5.1. Bidirectional Charging

Bidirectional charging remarks to the capability of an electric vehicle's charging system to both draw power from the grid (or another power source) and supply power back to the grid or other electrical loads [26]. This technology underpins various applications such as Vehicle-to-Home (V2H), where the EV supplies power to a home, and Vehicle-to-Load (V2L), where the vehicle provides electricity to specific devices or appliances.

The primary function of bidirectional charging is to offer flexibility in energy management for EV owners. For instance, during a power outage, an EV with bidirectional charging capability can power essential household appliances.

5.2. Vehicle-to-Grid (V2G)

Vehicle-to-Grid (V2G) is a technology that enables electric vehicles (EVs) to communicate with the power grid to sell demand response services by returning electricity to the grid or by throttling their charging rate. In principle, V2G allows EVs to act as mobile energy storage units, contributing to grid stability and efficiency. This bidirectional flow of energy is coordinated through advanced communication protocols and smart grid technologies, ensuring that energy is exchanged seamlessly without compromising the vehicle's primary function [27].

V2G systems are particularly beneficial in integrating more renewable energy sources into the grid. By storing excess energy generated during low-demand periods, EVs can supply power back to the grid during peak demand times, aiding in load balancing and reducing the need for additional power plants. This not only optimizes energy application but also provides economic incentives for EV owners through energy credits or reduced electricity costs [28].

5.3. Key differences

While both V2G and bidirectional charging involve two-way energy flow, their scopes and applications differ significantly. V2G is a specific application of bidirectional charging focused on the interaction between EVs and the power grid to provide grid services like load balancing and frequency regulation. It requires sophisticated communication systems and often involves regulatory compliance and partnerships with utility providers [28].

In contrast, bidirectional charging has a wider concept encompassing any scenario where an EV can both receive and supply electrical energy, not limited to interactions with the grid. Applications like V2H (Vehicle-to-Home) and V2L (Vehicle-to-Load) utilize bidirectional charging without necessarily involving grid services. While all V2G systems require bidirectional charging capabilities, not all bidirectional charging applications are designed for or involved in V2G activities [28].

5.4. AC Charging

AC Charging is a fundamental method for recharging electric vehicles (EVs) using the standard AC electricity from the power grid. In this process, the EV's onboard charger converts the incoming AC power to direct current (DC) to charge the battery. This method leverages existing electrical infrastructure, making it widely accessible for residential and public charging stations where vehicles can be charged over longer periods.

The charging power in AC Charging is limited by the capacity of the onboard charger and the electrical installation. Typical power levels range from 3.3 kW for single-phase connections to 22 kW for three-phase systems [29]. This setup is ideal for overnight charging or locations where vehicles remain parked for extended durations.

AC Charging is integral to Vehicle-to-Grid (V2G) applications by enabling bidirectional energy flow between electric vehicles (EVs) and the power grid through the vehicle's onboard charger, which can both receive and supply AC power. In AC V2G systems, the onboard charger includes an inverter that converts the DC power from the battery back to AC power compatible with the grid, allowing EVs to act as distributed energy resources. Using the EV’s power converter makes the required charging infrastructure minimal and cost-effective compared to DC bidirectional charging solutions. This integration facilitates services such as peak load management, frequency regulation, and renewable energy integration by providing additional storage capacity and flexibility to the grid [28].

Typical onboard chargers are composed by two stages of power conversion, in the first is performed the rectification and power factor correction. The second stage has the galvanic isolated DC-DC converter that provides the EV’s high-voltage battery with the requested charging voltage and current. Bidirectional chargers imply extra components or selection of different components, typically favouring transistors over unidirectional diodes. These additional components increase the cost of the onboard charger, but also its size and weight, which manufacturers are always looking to minimize. According to the literature, most of the bidirectional onboard chargers implement variants of bridgeless totem-pole boost AC-DC converter. The basic configuration of this circuit has two switching legs, a fast-switching one as boost converter and a slow-switching for rectification, operating at grid frequency. Two-channel and three-channel interleaved totem-pole can further improve the efficiency, reduce the output voltage ripple, and distribute the power among more switching cells, Figure 2 [30].

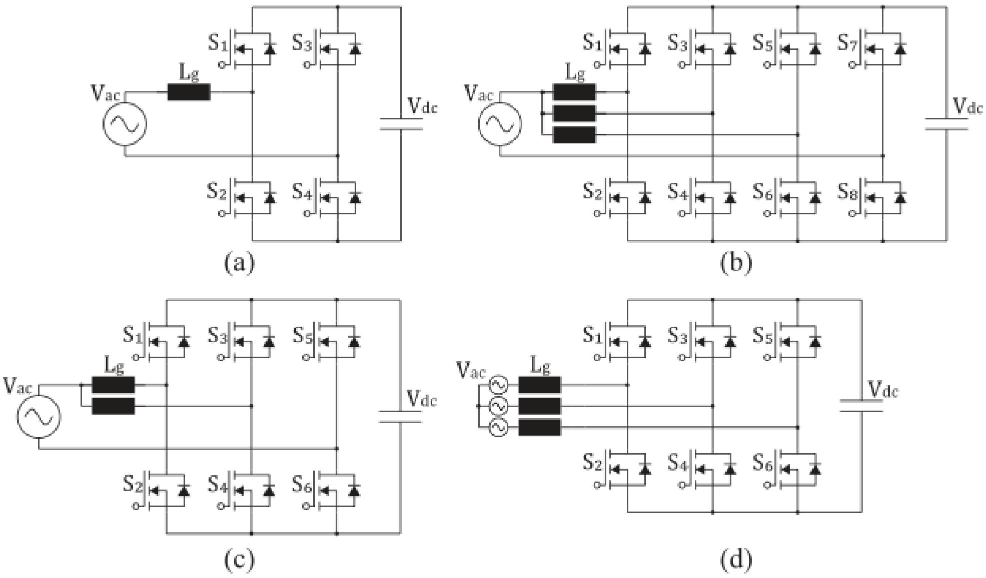

Figure 2 – AC-DC Power Factor correction converter topologies for two-stage onboard chargers: a) totem-pole; b) three-channel interleaved totem-pole; c) two-channel interleaved totem-pole; d) three-phase totem-pole [5].

Beyond of the configuration of the power converter, the switching devices used also have an important role in the performance of the onboard charger. Wide bandgap (WBG) semiconductors are gaining interest in the automotive industry, such as silicon carbide (SiC) and gallium nitride (GaN), as they offer superior properties compared to conventional silicon. SiC MOSFETs are used in high-power converters due to the superior breakdown voltage and thermal conductivity. This type of semiconductor can be implemented in 800 V battery systems without recurring multilevel topologies, as breakdown voltage rating between 600 to 1700 V are commercially available. The GaN switches are also an attractive solution for high-frequency and compact power converters with miniaturized passive components. WBG semiconductors are already being used in the EV market, mainly Tesla, where it uses SiC MOSFETs in the traction inverters. Regarding the onboard chargers, Lucid Air EV is the first to adopt WBG devices in its conception [30].

The current EV market with bidirectional onboard chargers is mostly focused in Vehicle-2-Load (V2L), where the EV battery is used to power some device connected directly to the charging port, but some do have higher ratings enabling more demanding bidirectional applications such as Vehicle-to-Home (V2H), Vehicle-to-Building (V2B) and Vehicle-to-Vehicle (V2V), Table 4 [30].

Table 4 – Current commercially available EVs with bidirectional onboard chargers.

Model	Year	Bidirectional application
Hyundai Ioniq 5	2021	V2L (3.6 kW)
Kia EV6	2021	V2L (3.6 kW)
Genesis GV60	2022	V2L (3.6 kW)
BYD Atto 3	2022	V2L (2.2 kW)
Ford F150 Lightning	2022	V2H, V2L (9.6 kW)
MG ZS EV	2022	V2L (2.2 kW)
Sono Sion	2023	V2L (3.7 kW)
GMC Hummer EV	2024	V2L, V2V (6 kW)

5.5. CHAdeMO

CHAdeMO is a DC fast-charging protocol for electric vehicles (EVs) that enables high-power charging through a standardized connector and communication method. Developed by the CHAdeMO Association, a consortium that includes major Japanese automakers and energy companies, the protocol facilitates efficient and safe charging by defining both the physical and communication interfaces between the EV and the charging station [31].

Technically, CHAdeMO supports charging at power levels up to 62.5 kW (500 V, 125 A), with newer versions of the protocol accommodating higher power to meet advancements in battery technologies. The protocol employs a dedicated DC charging connector, separate from the AC charging port, allowing for faster energy transfer directly to the vehicle's battery. Communication between the EV and the charger is established using a Controller Area

Network (CAN) bus, which coordinates the charging process by exchanging information on parameters such as voltage, current, and battery state of charge. This ensures that the charging station adjusts its output based on the battery's condition, optimizing efficiency and safety [31].

From the early days of CHAdeMO, EVs were recognized in Japan as emergency source of power supply, accelerating the development of bidirectional charging technology. In the year of 2012 Vehicle-to-Home systems with CHAdeMO were introduced to the market, and in 2013 the Ministry of Economy, Trade and Industry of Japan formed a working group and issued the first guideline of Vehicle-to-Home in March of that year. Following the publication of this guideline, the CHAdeMO association developed and released a certification test specification in March of 2015 [32].

CHAdeMO is considered to be the first bidirectional charging protocol with V2G functionality enabled, with mass-market production and the certification system in place to ensure interoperability across EVs and V2G devices. According to the CHAdeMO association data, currently there are 20 bi-directional commercial chargers models and over 10000 units installed [33].

5.6. CCS Combo (Combined Charging System)

CCS Combo (Combined Charging System) is a universal charging standard for electric vehicles (EVs) that consolidates both alternating current (AC) and direct current (DC) charging functionalities into a single connector. This integration allows EVs equipped with CCS Combo to utilize the same port for various charging needs, from slow AC charging at residential locations to rapid DC charging at public stations [26]. The connector combines the traditional Type 1 or Type 2 AC plugs with two additional DC pins, enabling high-power charging without the necessity for separate inlets. The system utilizes communication protocols based on Power Line Communication (PLC) between the EV and the charging station to ensure safe and efficient energy transfer, ISO 15118. This communication manages parameters such as voltage, current, and state of charge, allowing the charger to adjust its output based on the vehicle's requirements and optimize the charging process.

CCS Combo allows bidirectional charging but is not that mature compared to the other DC charging protocol, CHAdeMO, since its capabilities are newer and less widely deployed. The communication protocol ISO15118-20, which introduced enhanced support for bidirectional charging features was published in 2022 [34]. Recently, Volkswagen announced the adoption of this standard as introduced the new functionality of Vehicle-to-Home to its EVs through a software update (to specific EV models) [35]. Concerning EVSE, there are already commercially available solutions for DC bidirectional charging with CCS Combo, such as the Wallbox Quasar 2 [36] and Ambibox DC-Wallbox [37].

6. VESSEL CHARGING

Onshore charging and vessel propulsion systems are categorized as either AC or DC based on the type of electricity used on the busbar. If the vessel's main bus is DC, it is classified as a DC propulsion system [38], [39]. The most relevant charging standards are:

- IEC 60092-201: Covers general system design elements for electrical systems, including AC/DC distribution, earthing, protection, and motor circuits.
- IEC 60092-503: Specifies requirements for AC supply systems (1kV to 36kV), including insulation, electrical protection, high-voltage equipment, transformers, and converters.
- IEC/IEEE 8005-1: Defines standards for High Voltage Shore Connection (HVSC) systems (1MVA and above), addressing design, testing, installation, distribution, shore-to-ship connection, transformers, control, monitoring, interlocking, and power management.
- IEC PAS 8005-2: Covers Low Voltage Shore Connection (LVSC) systems (up to 1MVA) with similar topics as HVSC but for lower power requirements.

6.1. Wired Charging Systems

6.1.1. AC Charging Systems

AC Charging Systems: An AC charging station can be connected to both DC and AC propulsion systems, though each configuration presents unique challenges and requirements [39].

When an AC charging station connects to a DC-based propulsion system, the AC power is first converted to DC onboard using a converter (Figure 3). This converted power is supplied to a main DC bus within the system. If this converter effectively regulates voltage to meet battery requirements, an additional buck and boost converter (Figure 4) is unnecessary, leading to potential cost savings. The presence of multiple converters connected to a common point confirms the role of this central DC bus.

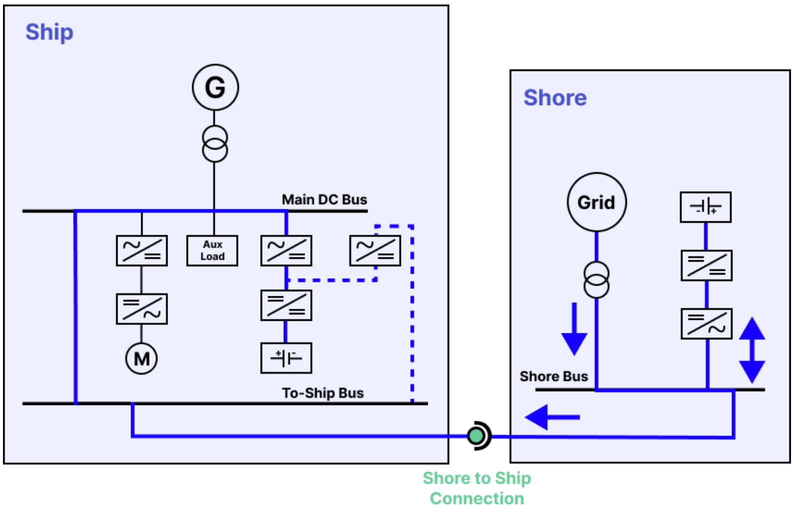

Figure 3 – AC Charging station connected to DC propulsion system [40].

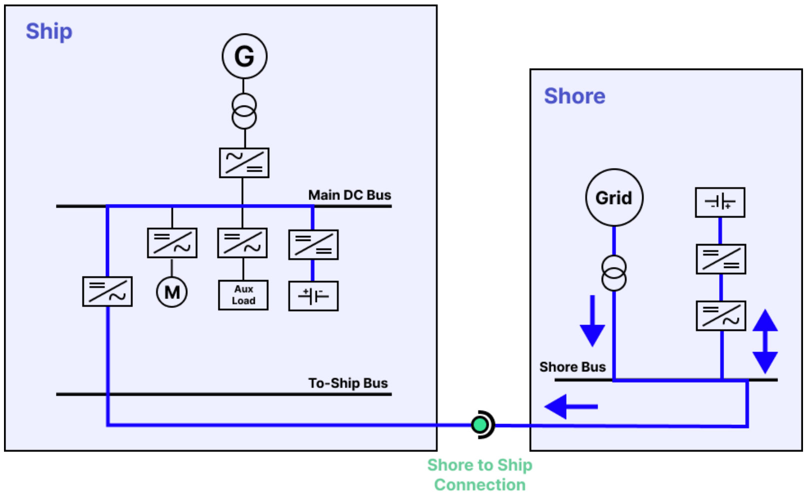

Figure 4 – AC Charging station connected to AC propulsion system [40].

For an AC propulsion system, the primary challenge lies in synchronizing voltage, phase, and frequency between the onboard system and the onshore charging station. This process is time-consuming, making it impractical for time-sensitive operations but well-suited for cold ironing, where vessels remain docked for extended periods. European systems often integrate 50/60 Hz frequency converters to improve synchronization efficiency and reduce energy losses (European systems reference [41].

AC charging systems offer a cost-effective and gradual charging solution, typically delivering up to 22 kW, with full charging taking approximately 8 to 10 hours. While gentle on batteries, AC charging can suffer from energy losses due to transformers and rectifiers. However, these systems can capitalize on off-peak electricity stored in onshore batteries, lowering costs and reducing grid strain [38].

6.1.2. DC Charging Systems

A DC charging station can be efficiently connected to both DC and AC propulsion systems, offering advantages in weight reduction, energy efficiency, and integration with renewable energy sources.

When a DC charging station connects to a DC propulsion system, the onshore station directly regulates and controls the incoming AC power, eliminating the need for onboard inverters/converters (Figure 5). This simplifies vessel design, leading to cost and weight savings [39]. Additionally, DC shore power systems reduce power conversion losses, improving vessel range and operational efficiency. Charging stations such as Aqua Superpower provide high output charging up to 350 kW, though most operate around 150 kW [1][4]. The "Future of the Fjords" catamaran, for example, uses a 1000V DC shore connection, demonstrating how DC charging enhances energy transfer efficiency in battery-electric marine transport [41].

For a DC charging station connected to an AC propulsion system, energy can be transferred directly to the onboard batteries without passing through the AC busbar, as seen in Figure 6. The onshore charging station transfers power to the buck/boost converter onboard, effectively bypassing one conversion step and reducing energy losses [39]. The incorporation of super-capacitors in DC charging systems further buffers power fluctuations and stores regenerative energy, enhancing system performance [42].

By minimizing conversion stages and leveraging high-voltage DC charging, DC shore power systems provide a more efficient and future-ready solution for electric and hybrid vessels.

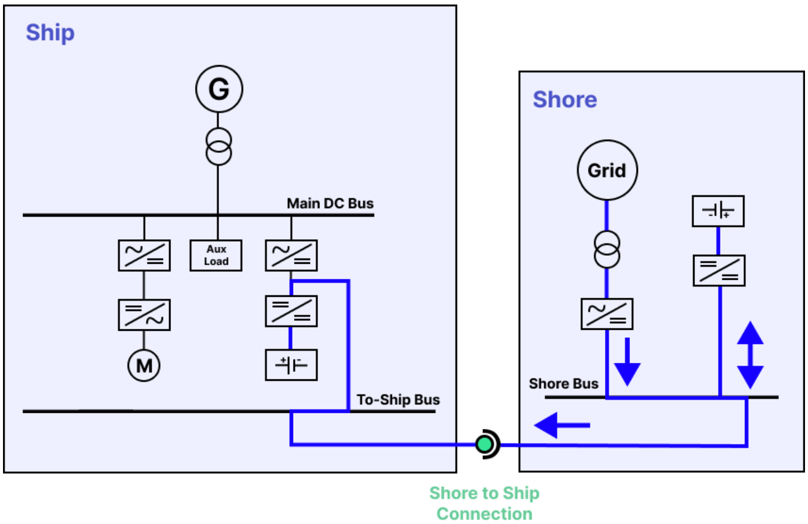

Figure 5 – DC Charging station connected to DC propulsion system [40].

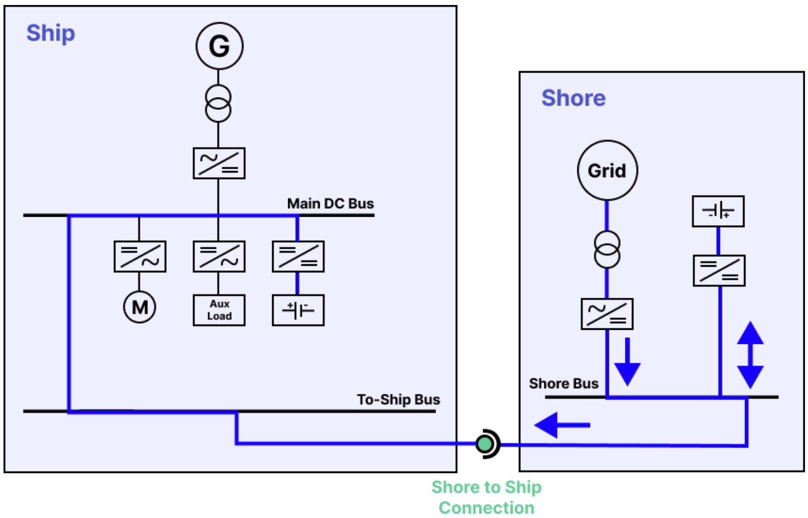

Figure 6 – DC Charging station connected to AC propulsion system [40].

6.2. Wireless Charging Systems

Wireless charging systems, also known as contactless power transfer, have gained significant attention for high-power applications in electrified transportation systems, medical devices, and consumer electronics. In the marine industry, wireless charging offers several advantages over traditional wired solutions. It eliminates the need for physical connections and disconnections, making it more time-efficient, especially in harsh weather conditions and saline environments. Additionally, wireless systems provide inherent galvanic isolation, reducing the risk of corrosion and wear on connectors, which are common issues with wired connections in marine vessels [40], [41].

Wireless charging operates through the transfer of energy via either an electric field (capacitive) or a magnetic field (inductive) between a transmitter and a receiver. While capacitive systems are often used for lower-power applications, inductive power transfer is more commonly applied in high-power charging systems, particularly in electrified transportation like marine vessels. In inductive charging, the transmitter and receiver coils work together similarly to a transformer, though with lower mutual inductance [40]. This results in the need for additional systems to manage the reactive power, improving efficiency and performance. One of the main benefits of inductive charging is its ability to provide galvanic isolation, eliminating the need for traditional onboard transformers. This reduces wear and tear and improves system reliability, making it a suitable choice for the marine industry [41].

Research efforts are exploring wireless charging technology to enhance power transfer and reduce charging times for marine vessels. For example, in Cornwall, UK, researchers from Marine-i and Perpetual Research Consultancy are working on very high-frequency (VHF) wireless charging, which aims to significantly improve charging efficiency for both manned and autonomous ships [40], [43]. Real-world implementations demonstrate the effectiveness of wireless charging. In Fredrikstad, Norway, a 100 kW wireless charging system has been integrated into a 15-meter electric ferry, enabling 145 charging sessions per day, each lasting around 112 seconds. Similarly, in Jektavik, Norway, a 1.5 MW wireless charging system with a retractable arm has been deployed for a ferry operating on a 3.5 km route, enabling automated and efficient power transfer [44].

6.3. Battery Swapping Method

Battery swapping has been widely explored as a rapid battery refuelling method for electric heavy-duty trucks and buses, making it a promising solution for short-distance ferries with critical docking times. Unlike traditional charging methods, which require extended periods at berth, battery swapping enables vessels to quickly exchange depleted onboard batteries for fully charged ones, significantly reducing downtime and improving operational efficiency [8]. This approach is particularly beneficial for inland waterway shipping, where electric vessels follow fixed routes and must coordinate battery swaps at designated ports to maintain safe charge levels throughout their voyage [45].

This method offers substantial advantages for the power grid as well. Since onshore battery packs can be charged gradually during off-peak hours or at a centralized charging station incorporating renewable energy sources such as wind and hydropower, the overall grid load is smoothed out. This helps avoid the high demand spikes associated with fast charging, ensuring a more stable and cost-effective electricity supply. Additionally, port-based battery swapping stations can provide peak shaving and valley filling services, helping to alleviate grid strain caused by the unpredictability of individual vessel charging behaviors [45]. Because stationary battery packs do not require high-power converters for immediate fast charging, they can be recharged overnight or over several hours, further reducing infrastructure strain [40], [46].

The study by Karami et al. [41] investigates three power system architectures for charging hybrid propulsion systems, both AC-based and DC-based, focusing on energy efficiency. By analysing load-dependent power loss models, the [40]study examines how energy efficiency is affected by load-sharing ratios between the onshore battery and the grid. The results conclude that DC charging and inductive charging are more energy-efficient than AC charging for ferries with AC propulsion systems. However, for ferries with DC-based onboard power systems, the most efficient charging method depends on specific charging parameters. Additionally, the study shows that wireless charging systems can provide nearly the same energy efficiency as conductive charging, justifying their use despite marginally lower energy transfer efficiency in some configurations.

6.4. Shore-To-Ship Interface

The shore-to-ship interface, essential for charging hybrid propulsion systems, consists of plugs and receptacles, cable management systems, mechanical structures, and monitoring systems. Traditionally, shore-to-ship connections, particularly for cold ironing, have relied on personnel manually carrying, connecting, and disconnecting heavy cables [40]. However, beyond physical connection, the interface also involves coordination between ship personnel and shore facilities to ensure smooth and safe operations. Effective management is critical for maintaining safety, efficiency, and regulatory compliance, with clear communication and structured information exchange being key to minimizing risks and ensuring success [47].

One of the simplest ways to establish the electrical connection between the ship and the charging station is through contact charging. This can be done by manually plugging a cable into the charging dock at lower voltages, or, for higher voltages, by automating the process using mechanical arms to engage the plug, enhancing safety [39]. Another method involves the use of an APS Tower, which involves dropping the charging cable from a height onto the vessel. The system uses a cable winch to adjust the plug's height based on tide levels, while actuating arms control its distance from the ship. A custom hatch on the ship’s hull opens when moored, allowing the plug to connect. This system is used on vessels like the MF Ampere and Elektra [48].

Contact charging, while straightforward, does have its challenges, especially when the vessel is not stationary due to varying water levels. A large wave could disrupt the connection, requiring the implementation of a vacuum mooring system to maintain a stable charging connection [39].

In more advanced systems, automated shore-to-ship connectors like the NG3 Plug are used for cold ironing and charging applications. This system operates by lowering a shuttle bar from the ship to connect to the shore-side connector and lifting the power socket to align with the ship’s socket. For instance, the Color Hybrid ferry uses this system, receiving 2.5 MW of night charging and 6.5 MW during the afternoon, streamlining the connection process and ensuring reliable energy transfer [40], [49].

As an alternative, the Flying Plug system offers a contactless solution. It utilizes the ship's mooring line to support a set of dollies, which bring the connector and power cables to the ship, facilitating a quick and efficient connection. The Flying Plug requires minimal crew involvement and reduces the need for extensive port infrastructure. With the ability to handle power exchange capacities of up to 13 MVA under 11 kV, this system offers versatility for vessels of varying sizes [44].

A more recent implementation is the wireless charging system used by the MF Foglesong; the world's first commercial ferry equipped with high-power wireless charging. Developed by Wärtsilä, the system is based on inductive power transfer and can transfer over 1 MW of electrical energy, 300 times more powerful than current chargers used for electric cars. This contactless solution eliminates the need for physical cable connections, ensuring safer, more reliable, and efficient energy transfer while reducing maintenance costs due to the lack of wear and tear on physical connections [40], [50].

7. SMART CHARGING INFRASTRUCTURE

The development of smart charging architectures for EVs, HDVs, and vessels is expected to undergo substantial advancements, driven by rapid technological innovation and the increasing demand for efficient, reliable, and sustainable transportation systems. This section provides a comprehensive evaluation of the current state and prospects of AC and DC charging technologies, alongside the identification of emerging trends and advancements shaping the evolution of smart charging architectures.

The current landscape of AC and DC charging technologies highlights their distinct roles within the EV ecosystem. As of 2024, AC chargers predominantly operate at power levels below 30 kW (Level 1 and Level 2 Charging), making them ideal for scenarios where vehicles are parked for extended durations. Projections indicate AC charging will dominate in volume, with ~66% of public charging points installed between 2024–2034 relying on this technology, driven by its adaptability to renewable energy integration and lower grid strain [51], [52].

In contrast, DC fast charging (Level 3 Charging) has experienced significant expansion, particularly within public charging networks. DC chargers typically operate at power levels of 50 kW or higher, with some ultra-fast chargers delivering power exceeding 350 kW. This technology addresses the need for rapid charging, especially for long-distance travel and high-utilization vehicles. The market for DC charging systems is anticipated to grow substantially, with an estimated market value of $23.7 billion by 2029 [53]. Within this segment, very high-power chargers (150–350 kW) are expected to capture a dominant share, reflecting the increasing demand for faster and more efficient charging solutions.

The future of smart charging architecture is poised for transformative advancements, driven by innovations in power electronics, artificial intelligence, and grid integration. Key trends shaping the evolution of smart charging systems are in advances in power electronics, bidirectional charging and V2G, artificial intelligence and machine learning integration, smart grid integration, ultra-fast charging technology and novel charging technology [54], [55], [56], [57], [58].

Advances in power electronics, particularly the adoption of silicon carbide (SiC) MOSFET devices in DC chargers, are enabling the development of more efficient and compact charging solutions. These devices offer superior thermal management, reduced energy losses, and higher breakdown voltages of up to 1200V, contributing to smaller charger footprints and improved performance. By integrating SiC MOSFETs, DC fast chargers can achieve peak efficiencies beyond 98.5% at power densities of 8kW/L, when compared to 2-4 kW/L of current silicon IGBTs, making them a crucial aspect in smart charging technology [59], [60], [61].

Bidirectional charging technologies, encompassing Vehicle-to-Grid (V2G), Vehicle-to-Home (V2H), and Vehicle-to-Everything (V2X) capabilities, are emerging as critical components of smart charging systems. These technologies enable EVs to operate as mobile energy storage units, supporting grid stabilization and renewable energy integration. While still in the early stages of deployment, recent developments in charging standards, particularly ISO 15118-20, are accelerating the adoption of bidirectional charging. By Summer 2025, all newly installed or renovated public EV charging points must support ISO 15118-1 through ISO 15118-5, and from January 1, 2027, all new and refurbished public charging points and new private charging points must support ISO 15118-20 [62]. ISO 15118-20 introduces Bidirectional Power Transfer (BPT), Wireless Power Transfer (WPT), and Automatic Connection Device (ACD) support [63]. Moreover, smart charging systems optimize the charging process to ensure economical usage of electricity and minimize the impact on the electrical grid. These systems leverage real-time data on electricity prices, grid conditions, and renewable energy generation to strategically schedule EV charging. This approach not only reduces electricity costs for consumers but also enhances the integration of renewable energy sources, contributing to a more sustainable energy system.

Artificial intelligence and machine learning are set to revolutionize smart charging through predictive maintenance, dynamic pricing models, and real-time load balancing. These technologies can enhance the reliability and efficiency of charging networks by leveraging advanced data analytics and intelligent decision-making algorithms. With a higher degree of smart sensors, predictive maintenance systems can analyse data and monitoring systems installed in charging stations to detect anomalies and predict potential equipment failures. By continuously monitoring the health and performance of charging infrastructure, these algorithms can identify patterns and trends that indicate impending issues. This proactive approach allows operators to schedule maintenance activities before failures happen, reducing downtime, improving reliability, and extending the lifespan of charging stations. Moreover, these algorithms enable very complex dynamic pricing and real-time load balancing models for EV charging by considering factors such as time of day, electricity demand, and the availability of renewable energy. Additionally, this opens the realm of the possibility of smart charging systems can learn individual preferences, charging patterns, and even driver behaviour [64], [65].

Ultra-fast charging technologies are becoming a focal point for the electrification of HDVs and long-distance travel. Chargers delivering power levels exceeding 350 kW are under development, with megawatt-scale charging systems (up to 3.75 MW) being standardized for HDVs. These advancements aim to minimize charging times and support the rapid adoption of electric HDVs. These fast-charging stations (and the large deployment of EVs) can increase peak load and cause voltage deviations, harmonics perturbations and phase imbalances. Thus, the integration of smart charging systems with smart grids and renewable energy sources is expected to enhance grid stability. Real-time adjustments in charging speeds, based on grid demand and renewable energy availability, will optimize energy consumption and facilitate the increased use of renewable energy for EV charging with the aid of energy storage systems and renewable energy incorporated in high power demand stations [66].

Automated static and dynamic charging solutions can maximize the charging time during operation, therefore reducing reliance on large battery capacities. These solutions include the use of parking pads for automatic charging (static) and continuous charging via road-embedded infrastructure. From a vehicle design perspective, continuous charging enables EVs to operate with 40–70% smaller batteries, lowering manufacturing costs by ~35% per kWh and reducing lifetime carbon footprints by 18–25% due to decreased lithium and cobalt usage. Smaller batteries also experience less thermal stress, extending cycle life by 20–40%. However, challenges persist. Infrastructure costs vary significantly (Inductive systems can cost up to 2 million EUR/ km) and maintenance demands differ too, with conductive systems requiring frequent upkeep due to wear-prone contacts, whereas inductive components, buried underground, incur lower long-term costs. Electromagnetic interference (EMI) in wireless systems necessitates shielding to protect vehicle electronics which increases the price further. Emerging innovations aim to address these limitations with advances in materials, such as high permeability nanocrystalline ferrites, have pushed inductive coupling efficiency to >92% in lab settings. Autonomous EVs could further optimize this technology by routing themselves to charged road segments, maximizing operational uptime [67], [68], [69].

The evolution of smart charging architecture is integral to the transition toward a sustainable and electrified transportation sector. Continued research, standardization efforts, and cross-sector collaboration will be essential to realize the full potential of these technologies, ensuring their scalability and effectiveness across diverse use cases. For EVs, the widespread adoption of both AC and DC charging solutions, enhanced by AI-driven optimization and V2G capabilities, is expected to support the increasing electrification of passenger vehicles. For HDVs, the deployment of dedicated megawatt-scale charging infrastructure will be critical to addressing the unique energy demands of heavy-duty transportation. In the maritime sector, the adoption of shore-to-ship power solutions and high-capacity charging systems for electric ferries and short-sea vessels will play a pivotal role in decarbonizing port operations and maritime transport.

8. HIGH-POWER DC CHARGING FOR HEAVY-DUTY VEHICLES (HDVS) AND VESSELS

8.1. Methods of Fast Charging:

Battery charging methods differ depending on the application requirements alongside battery chemistry and performance specifications. Such as the Constant Current Constant Voltage (CCCV) charging approach first uses a constant current which switches to a constant voltage to provide safe and efficient charging for lithium-ion batteries. The Constant Power Constant Voltage (CPCV) charging process starts with high constant power before transitioning to constant voltage to enhance charging speed for large capacity systems. Burst Charging (BC) delivers electrical currents in short intervals followed by brief pauses to improve chemical stability and extend battery lifespan. Trickle charging keeps battery levels stable by supplying a low steady current that compensates for natural self-discharge. In taper current charging the current reduces automatically as battery voltage increases which makes this method common for basic lead-acid chargers. During rest intervals burp charging uses short discharge pulses to eliminate gas bubbles from electrodes and enhance their performance. IUI charging uses constant current followed by constant voltage and ends with an equalizing charge to balance lead-acid battery cells. Float charging sustains full battery capacity by holding voltage below its maximum threshold [70]. In addition, [71] instead of transitioning to constant voltage charging, multi-stage constant current (MSCC) employs multiple steps with decreasing charging currents. The charging current decreases each time the battery hits its predefined voltage limit until it finally reaches full charge at maximum voltage with minimal current. The Non-Linear Voltammetry solution uses an invention that features a fast-charging system based on Non-Linear Voltammetry which adapts charging with non-linear voltage variations and relaxation patterns for battery condition optimization and maximized charge capacity [72].

The best methods for fast power DC charging currently involve CPCV, CCCV, and MSCC approaches. For rapid charging of large-capacity systems CPCV provides an optimal solution because it starts at high power levels before shifting into a controlled voltage phase. The CCCV method has gained widespread acceptance for its efficient nature which ensures rapid and secure charging performance and thus it serves as the standard in numerous lithium-ion applications. The MSCC technique achieves better thermal handling and charging performance by reducing current step by step which makes it appropriate for complex systems. Non-Linear Voltammetry demonstrates potential because it adjusts dynamically to changing battery states while still being primarily experimental. Traditional charging methods including Burst Charging, Taper Charging, Burp Charging, IUI, Float, and Trickle Charging fail to meet fast charging demands because they focus on battery longevity and maintenance with lead-acid chemistry compatibility instead.

8.2. First Charging Standard

The increasing global presence of fast chargers created the need for multiple charging standards to be developed. The establishment of global standards for ultra-fast charging systems has occurred because of the need for consistency. Currently, four major ultra-fast charging standards dominate the world, each with its own unique connector: CHAdeMO, CCS, Tesla, and GB/T. The standards IEC 62196-3, IEEE 2030.1.1, GB/T 20234.3, and SAE J1772 define these systems [71].

The CHAdeMO protocol which originates from Japan stands as a common ultra-fast charging standard providing power levels from 6kW up to 400 kW [73]. The Combined Charging System (CCS) protocol was jointly developed by SAE International (Society of Automotive Engineers) and the European Automobile Manufacturers Association (ACEA) in 2011 added DC. Tesla's proprietary ultra-fast charging protocol operates exclusively through Tesla Superchargers and vehicles and delivers power up to 250 kW [74]. The GB/T protocol, specifically GB/T 27930 functions exclusively within China's charging infrastructure. China is collaborating to develop a new CHAdeMO standard which will work across different regions and achieve charging power up to 1200 kW while ensuring compatibility with both GB/T and CCS standards. The Charging Interface Initiative (CharIN) established the Megawatt Charging System (MCS) Task Force in 2018 to develop a standardized high-power charging solution for large battery electric vehicles used in heavy-duty trucks and commercial applications. The Megawatt Charging System (MCS) designed for electric trucks and buses has been launched by CharIN to deliver charging power up to 3.75 MW [75]. A comparison is shown in Table 5.

Table 5 – First Charging standard modified from [71].

Type	Compliant standards	Region	Max voltage (V)	Max current (A)	Max power (kW)
CHAdeMO	IEEE 2030.1.1 IEC 62916-3	North America; Japan; Europe	1000	400	400

Type	Compliant standards	Region	Max voltage (V)	Max current (A)	Max power (kW)
CCS Combo 1	SAE J1772 IEC 62916-3	North America; Japan	600	400	200
CCS Combo 2	IEC 62916-3	Europe	900	400	350
Tesla	No associated items	North America	500	631	250
CHAdeMO (ChaoJi GB/T)	GB/T 20234.1(DC (20234.3-2023)	China/Japan	1500	800	1200
MCS	No associated items	-	1250	3000	3750

Like HDV, vessels charging protocols are not mature enough to have single standard. Different work and people are testing different protocols like CCS2, CHAdeMO [76] which are used for vessels charging as well as other charging protocols established for vehicles. Kumar and Panda [77] work on developing a shore-to-ship charging system (PQICI) or multipurpose and power quality improved cold ironing (MPQI-CI) which delivers megawatt-range power through AC and DC modes. The PQICI protocol functions with various wiring layouts and can operate at both 50 and 60 Hz frequencies. The system can power four vessels at once and achieves harmonic control goals defined by IEEE 519 standard. MPQI-CI systems for platform supply vessels enable multipurpose operation by converting standard three-phase 415 V AC shore power into stable 690 V DC output, which aligns with the typical onboard bus requirements. This DC-based cold ironing not only allows efficient shore-to-ship power transfer but also supports flexibility in vessel compatibility, accommodating diverse DC bus voltages.

8.3. Technical Limitations and Challenges

Power electronics reliability and thermal management present major engineering challenges for high-power DC charging systems. The approach of charging currents to 3000 amperes demands proper thermal regulation to maintain operational safety and stability. Inadequate cooling solutions create excessive heat buildup which results in component degradation and reduced efficiency while risking total system failure. Studies by Tolbert et al. [9] and Balachandran et al. [78] stresses that ultra-fast charging systems require sophisticated thermal solutions to manage associated risks. Semiconductor devices made from materials like silicon carbide (SiC) and gallium nitride (GaN) produce converters with enhanced efficiency and power density. Alatise et al. [79] have reported that under high-voltage and high-frequency conditions the operational stability of the devices can be compromised by thermal stress. The elimination of these limitations stands as a crucial step toward enabling safe and scalable implementation of ultra-fast DC charging systems.

In addition to these limitations vessels has extra problems to connect to shore due to cathodic protection, flammable product and ship–shore bonding and electrical safety [80]. DC charging for vessels is difficult because onboard vessel systems operate at widely varying voltages, typically between 400 V and 1500 V, requiring charging stations to handle a broad voltage range efficiently and reliably [81].

9. WIRELESS AND AUTOMATED CHARGING

9.1. Automated Charging

The automotive industry is currently going through a massive transformation, triggered by electrification, autonomous driving, user-centric design and the challenge to connect the mobility and energy sector. A key technology in this transformation is automated (or hands-free) charging. It allows a non-invasive charging infrastructure for electric vehicles, especially in densely populated areas, represents a prerequisite for the advance of autonomous driving functionality, enables a truly user-centric car and is key for a smart and sustainable energy grid, that can cope with fluctuations of increasingly used renewable energy sources like solar and wind.

Summarized there are three main reasons for automated charging, collected in next subsections.

9.1.1. Next Level User Experience

Automated charging relieves from the burden of dirty cables & charging cards & is the next logical step towards a user-centric car, see Figure 7.

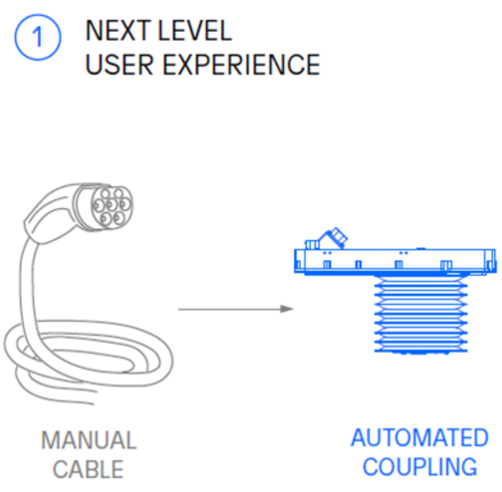

Figure 7 – User Experience by automated coupling the EV to the grid

9.1.2. Smart Grid Integration by High Vehicle Connectivity

For becoming a controllable resource for the grid, EVs must be connected whenever parked. Figure 8 illustrates how connecting EVs to the grid can help flatten the overall energy demand curve through controlled and time-shifted charging strategies. This requires a fully automated charging process.

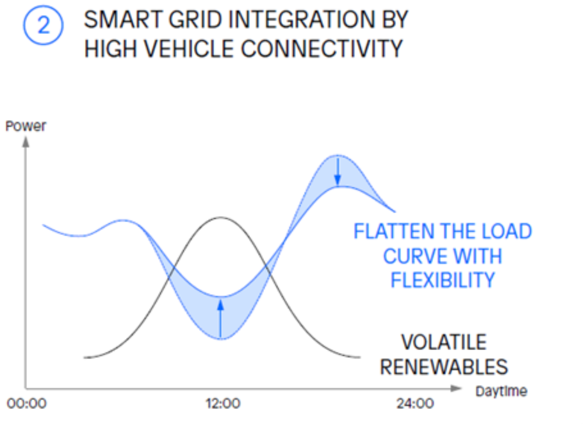

Figure 8 – Smart grid integration of EVs into the grid

9.1.3. Support of Vehicle Autonomy

Automated charging is a prerequisite for autonomous driving & parking. By 2030 70% will support parking features (level 2+) as Figure 9 suggests.

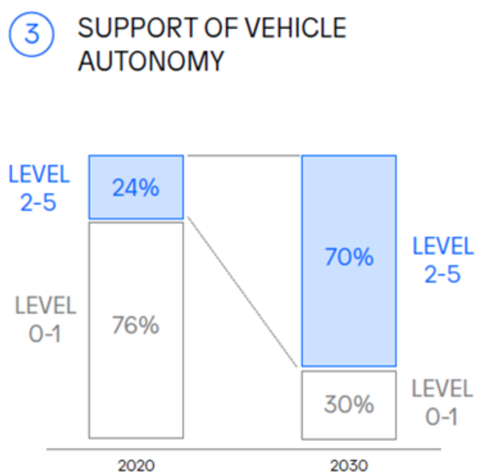

Figure 9 – Vehicle autonomy forecast

9.1.4. Possible Automated Charging Solutions

There are four main approaches to automated charging (see Figure 10): conductive robot-side, conductive robot bottom-up, wireless charging, and conductive charging bottom-up. The conductive robot-side method features high system costs based on its complexity and low robustness due to mechanical complexity, while the conductive robot bottom-up approach offers moderate costs but still faces durability challenges. Wireless charging eliminates physical connections, enhancing robustness and reducing maintenance, though efficiency can be a concern. Conductive charging bottom-up provides a direct connection from the ground, balancing cost and efficiency. Due to their superior robustness, only wireless charging and conductive bottom-up charging are considered viable for further investigation.

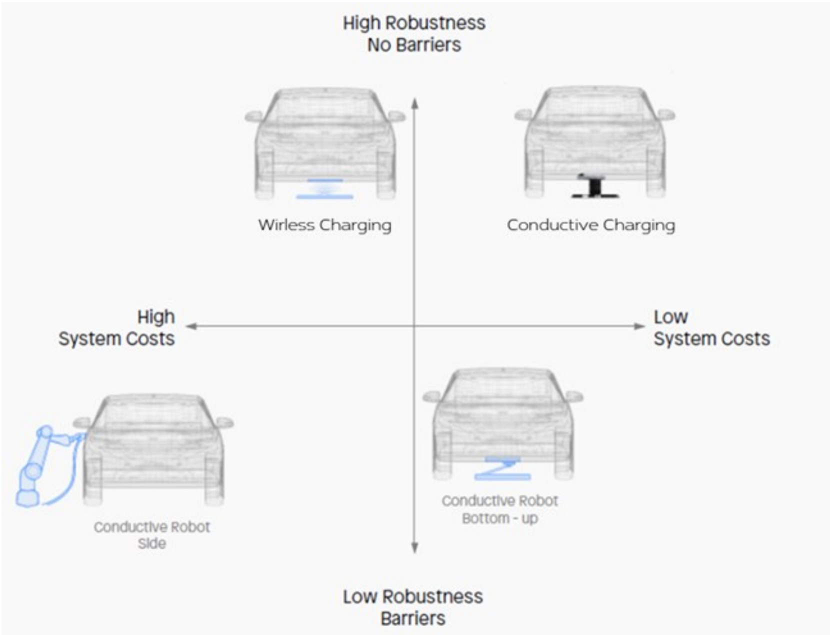

Figure 10 – Various automated charging solutions compared based on robustness and system costs

Definition Inductive Charging: Sometimes referred to as Wireless Charging, inductive charging transfers electrical energy via an airgap. It converts the grid frequency to a very high frequency (e.g., 85kHz) which allows a transmitter coil in the ground unit to produce a magnetic field which then induces current in a receiver coil in the vehicle unit. This technology is mostly known from charging mobile devices or the electrical toothbrush.

Definition Conductive Charging (e.g. Matrix Charging by Easelink): In contrast to Inductive charging, a physical connection is established for the energy transfer – the same as for manual charging cables for electric cars, as found in charging stations today. The only difference is that the charging process is fully automated and does not require any user interaction whatsoever. As soon as the vehicle is parked above a charging Pad, a connector is lowered from the vehicle's underbody and physically connects to the charging pad to charge the battery.

The two main technological concepts for hands-free charging currently pursued in the mobility industry are inductive and automated conductive charging.

A comparison of the key factors costs, efficiency and system complexity is shown below.

Costs: Competitive cost is a crucial factor in the automotive industry, especially for large-scale adoption. Conductive systems are approximately 70% cheaper than inductive charging due to its direct connection to the vehicle's existing Onboard Charger (OBC), eliminating the need for additional power electronics. Inductive charging requires expensive wire, cooling systems, shielding, and sophisticated sensors, significantly increasing costs—especially for bidirectional charging, where costs can be up to 4x compared to conductive systems (Figure 11).

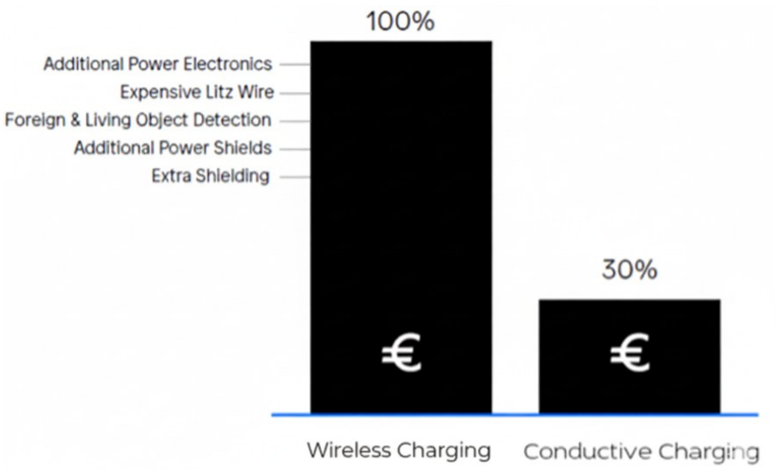

Figure 11 – Manufacturing cost comparison of wireless vs. Conductive automated charging systems

Efficiency: Conductive charging systems, achieve a high efficiency of >98%, while inductive charging typically reaches 85-90% in ideal conditions, compared to Figure 12. The lower efficiency of inductive charging is caused by weak magnetic coupling, misalignment between transmitter and receiver coils, and increased losses in bidirectional charging. Given the industry's focus on improving powertrain efficiency, the 5-10% efficiency advantage of conductive systems makes them a more attractive solution.

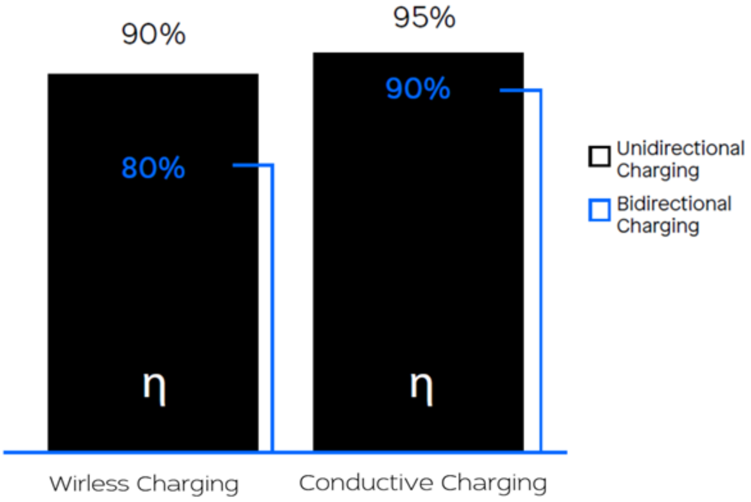

Figure 12 – Efficiency comparison between wireless and conductive charging

System Complexity & Weight (see Figure 13): A conductive system is lighter (5kg vs. 14kg for inductive charging) and simpler to integrate into vehicle architectures. Inductive charging requires large coils, shielding, cooling, and additional sensors, making it more complex and bulkier. Conductive systems do not need cooling, aluminum shielding, or complex safety sensors, making it easier to integrate into existing electrical/electronic (E/E) architectures while maintaining lightweight design principles crucial for automotive applications. However, a key advantage of wireless (inductive) charging is the lack of moving parts, which reduces mechanical wear and increases system durability over time.

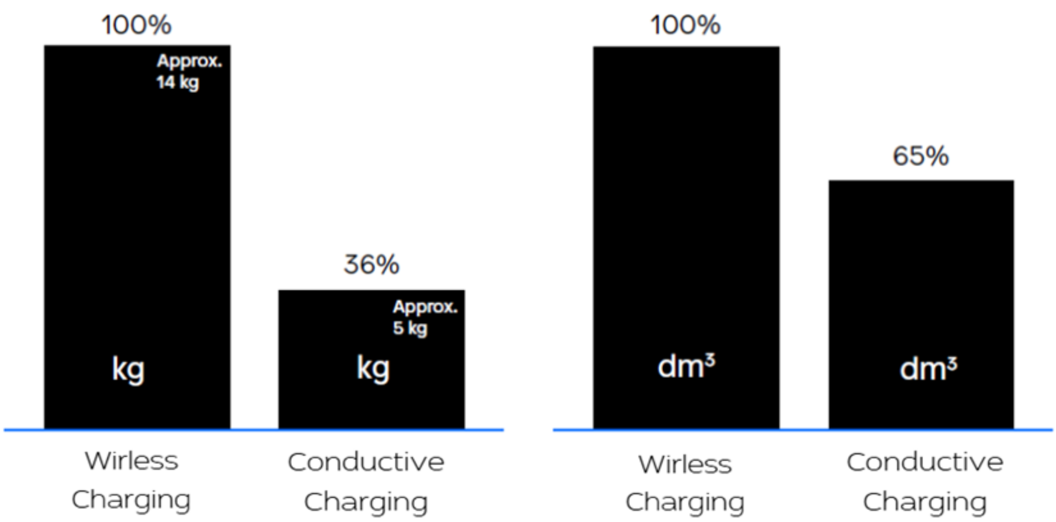

Figure 13 – Weight and size comparison between wireless and conductive charging systems

10. CHARGING HUBS AND ENERGY ECOSYSTEMS

EV sales are expected to accelerate in both developed and emerging markets, increasing the urgency for well-developed charging networks. The evolution of charging hubs signals a shift beyond basic vehicle charging toward multifaceted energy ecosystems that integrate renewables, storage, and intelligent software solutions.

The following paragraphs explore the major trends shaping the future of these charging hubs, including:

- Developments in high-power, ultra-fast charging systems.
- Interplay between renewable energy, on-site generation, and battery storage.
- The role of policy and regulatory drivers.
- Emerging business models and consumer engagement strategies.

10.1. Technological Advancements

10.1.1. High-Power and Ultra-Fast Charging

With modern battery packs supporting larger capacities, there is growing demand for ultra-fast charging (150 kW, 350 kW, and beyond). These solutions aim to reduce charging times to under 20 minutes, meeting the need for convenience and rapid energy replenishment. Academic studies suggest that advances in charging infrastructure can help alleviate range anxiety for both private vehicle owners and fleet operators (IEEE Transactions on Transportation Electrification, 2021).

10.1.2. Smart Integration with Renewable Energy

Charging stations increasingly pair on-site solar power or other renewable generation with energy storage systems, creating self-sufficient microgrids. This helps avoid spikes in grid demand and can provide additional revenue streams through energy arbitrage and grid services, such as load balancing. As the installation of intermittent energy sources grows, intelligent coordination between charging hubs and grid operators becomes more important to maintain system reliability.

10.1.3. Battery Storage and Grid Resilience

On-site battery systems can offset grid stress by storing excess energy for use during peak hours. This approach makes it possible to provide stable, predictable charging rates while reducing costs associated with drawing high volumes of electricity from the grid at peak prices. Research consistently demonstrates that coupling distributed generation with storage not only reduces carbon footprints but also secures the availability of power when grid supply is constrained (IEA, 2021).

10.1.4. Smart Charging Innovations

In regions like the Netherlands and Belgium, smart charging hubs are becoming increasingly prominent, particularly in the Netherlands where grid congestion poses a significant challenge. This issue stems from an outdated grid infrastructure struggling to keep pace with rising energy consumption. Simultaneously, renewable energy sources, such as solar and wind, have surged in recent years, leading to input peaks during sunny or windy days that further strain the grid. Smart charging technologies are being deployed to address these challenges by balancing demand and supply effectively, ensuring a more stable and resilient energy system.

For instance, initiatives in these countries focus on optimizing energy consumption through smart charging techniques, which can help manage grid challenges caused by rising electric vehicle demand. These strategies align with broader trends in energy management, where intelligent coordination between charging hubs and grid operators is crucial for maintaining system reliability. Similar to the integration of renewable energy and battery storage, smart charging innovations can enhance grid resilience and support sustainable transportation solutions (IEA, 2021).

10.1.5. Examples of Grid Resilience

Several examples **beyond V2G**, as V2X hasn't been practiced perfectly on a mass scale, apart from local micro grid use cases such as Sirius by Wallbox in Barcelona [82], demonstrate how charging hubs enhance grid resilience through smart energy management and infrastructure design:

- Dynamic Load Management

In the Netherlands, grid operators have implemented peak-shaving strategies by temporarily disabling public charging points during high-demand periods (4 PM–9 PM) to prevent grid overload [83]. This approach, combined with smart energy management systems, allows operators to charge up to 6× more EVs compared to unmanaged charging while reducing infrastructure upgrade costs [84]. For instance, The Mobility House optimized a school district's electric bus charging strategy, slashing peak capacity requirements by 75% (from 317 kW to 79 kW) through intelligent scheduling aligned with off-peak rates [85]. Many, many examples of dynamic load management charging sites or hubs are currently up and running throughout Europe, where in countries like Denmark and Lithuania, dynamic pricing at public charging points is becoming increasingly common [86].

- Cluster-Based Load Balancing

Advanced charging hubs use master-controlled clusters to dynamically distribute power among connected EVs. A master unit adjusts charging rates across a group of vehicles every 15 minutes based on real-time grid capacity, preventing overloads without sacrificing charging availability. This system prioritizes vehicles with urgent energy needs while maintaining voltage stability across distribution networks [87].

- Renewable Integration and Storage

Charging hubs increasingly pair solar generation with battery storage to create self-sufficient microgrids. For example, the U.S. National Renewable Energy Laboratory (NREL) developed a DC hub platform integrating 660-kW grid-tied inverters, 175-kW DC-DC converters, and photovoltaic systems. This setup decouples charging loads from grid dependency, ensuring stable power delivery even during outages [88].

- Grid-Interactive Technologies

Two-stage power converters and dual-loop controllers regulate voltage fluctuations caused by high-power chargers. These systems mitigate voltage sags by dynamically adjusting active power draw, maintaining stability even when EV charging spikes occur [89].

These strategies highlight how charging hubs are evolving into grid-supporting assets through proactive load management, renewable hybridization, and advanced power electronics.

10.1.6. Policy and Regulatory Factors

Standards organizations continue to push for harmonized charging protocols (e.g. ISO 15118, OCPP 2.1 by the OCA) to ensure interoperability among different vehicle makes, charging networks among charging hubs and energy ecosystems.

These regulatory measures also highlight the value of vehicle-grid integration (V2G). By enabling bidirectional energy flow between vehicles and the grid, policymakers and utilities can strengthen grid stability, enhance renewable energy utilization, and create new revenue streams for EV owners who choose to participate in demand-response programs (UK Department for Transport, 2020).

However, there are currently bottlenecks in many areas for adoption of the full iso15188 standard, including plug and charge challenges for payment purposes, as well as the full debate around V2G that has many elements which will take years to solve. Mainly as there is a requirement for unification from carmakers, grid operators and policymakers on a European level.

10.2. Business Models and Ecosystem Partnerships

10.2.1. Charging-as-a-Service (CaaS)

In the Charging-as-a-Service model, operators provide end-to-end solutions—installing and maintaining hardware and software in exchange for subscription fees or usage-based payments. This lowers barriers to entry for fleet owners and real estate managers who want to offer charging without directly managing the infrastructure.

10.2.2. Integration with Retail and Consumer Amenities

Modern charging hubs may house cafes, lounges, and co-working facilities to enhance driver experience, making the charging stop more engaging and comfortable. Some also integrate e-commerce pickup points or contactless payment systems to streamline travel convenience [90].

10.2.3. Energy Aggregation and Ancillary Services

Innovative operators are exploring ways to participate in energy markets by aggregating stored EV battery capacity. This aggregated power can be sold back into the grid during peak demand, creating ancillary service revenue. As the number of EVs increases, aggregated storage could significantly influence grid management practices.

EVs can provide several ancillary services to the grid:

1. Frequency Regulation: The rapid response capability of EV batteries can help maintain grid frequency within acceptable limits (12).
2. Voltage Support: EVs can inject or absorb reactive power to help maintain voltage levels in the distribution system (12).
3. Spinning Reserve: Aggregated EVs can act as a fast-responding reserve to cover unexpected drops in generation or increases in demand (13).

10.2.4. Emerging Challenges

- **Infrastructure Investment**: Building large charging complexes requires high upfront costs, often necessitating public-private partnerships or government grants to become financially viable. Also, the need for smart meter roll-out in some European countries is a significant obstacle to utilizing flexible devices for reducing energy bills and supporting the electricity grid. As of 2022, only 54% of EU households had smart meters installed, falling short of the 80% target set for 2020 [91]

- **Grid Upgrades**: High-power stations can stress existing electrical infrastructure, requiring upgrades to local transformers and distribution networks. This will take billions of euros to resolve [92].
- **Equitable Access**: Rural areas, multi-unit dwellings, and economically disadvantaged communities risk being left behind if policy and market forces priorities urban or wealthier locations.
- **Cybersecurity Concerns**: Connected infrastructure introduces potential vulnerabilities. Charging networks must protect against hacking attempts, data breaches, and other forms of cyber-based disruption (IEEE Cybersecurity for Smart Grid, 2021).
- **Fragmented Implementation**: While the European electricity market is highly integrated at a high level, not all countries have fully implemented EU regulations and directives, particularly regarding consumer and local flexibility provisions [91].

11. REGULATORY SUPPORT AND INTEROPERABILITY

11.1. Regulatory Frameworks for Light-Duty Electric Vehicle

The regulatory landscape for passenger EV charging is the most established segment of the electric mobility sector, providing a foundational blueprint and valuable lessons. Government strategies are the principal drivers behind the global expansion of public EV charging infrastructure. A comparative analysis of regional approaches reveals distinct philosophies and mechanisms; all aimed at solving the foundational challenge of guaranteed end-users have a reliable place to recharge. Major global governments are directly funding foundational EV charging networks. In North America, the U.S. has committed over $7.5 billion through the Bipartisan Infrastructure Law and Inflation Reduction Act. Key programs include the $5 billion National Electric Vehicle Infrastructure (NEVI) Formula Program to build a national DC fast charging network along major highways and the $2.5 billion Charging and Fuelling Infrastructure (CFI) Grant Program for community and rural charging projects [93], [94].

The EU uses the Alternative Fuels Infrastructure Regulation (AFIR) to legally mandate member states' build-out of EV charging. This regulation requires DC fast charging stations every 60 kilometres on main transport corridors by 2026 and links required public charging capacity (1.3kW) to each registered EV [3]. On the other hand, China uses a centralized, state-driven policy to aggressively build out EV charging infrastructure, making it the world leader with over 2 million public EVSEs. In contrast, Taiwan's government prioritizes creating a dense network of battery swapping stations to support its dominant electric scooter market [95].

11.2. Policy Impact on AC vs. DC Deployment

An effective national charging strategy is not a matter of choosing between AC and DC, but of fostering a symbiotic system where each technology plays to its strengths. Policies are increasingly reflecting this nuanced understanding. The U.S. NEVI program, for instance, specifically mandates DCFC along highway corridors to enable long-distance travel, while the complementary CFI program allows funding for Level 2 AC chargers in communities to support local charging needs [96], [97]. Global deployment data reveals different strategic priorities. China has aggressively built out both slow and fast charging networks. Europe, with a strong existing base of public AC EVSEs, is now using the AFIR mandate to build out its DCFC highway network [95]. In contrast, New Zealand has prioritized DCFC from the outset, resulting in the world's highest ratio of fast-to-slow public EVSEs, while the Netherlands has focused on creating a dense network of AC EVSEs for urban use. Recent research underscores the value of this balanced approach, showing that deploying slow public AC EVSEs in dense residential areas can reduce grid costs by up to 40% and increase end-user satisfaction by better matching long parking durations, complementing the role of DCFC for rapid recharging [95].

11.3. Smart Charging, Vehicle-Grid Integration (VGI), and Vehicle-to-Grid (V2G)

The rise of VGI and V2G is forcing a convergence of two historically separate regulatory domains: transportation and energy. An EV with V2G capability is no longer just a vehicle; it is a Distributed Energy Resource (DER), like a rooftop solar panel or a stationary battery. This means it must interact with complex wholesale and retail energy markets governed by entities like Public Utility Commissions (PUCs) and the Federal Energy Regulatory Commission (FERC) [98]. Widespread V2G deployment is currently hindered by significant regulatory barriers, including a lack of standardized utility interconnection rules for mobile assets and the absence of established market structures to properly compensate EV owners for the grid services they provide. Developing a coherent regulatory framework that bridges the transportation and energy sectors is a profound structural challenge for governments [99].

11.4. Cybersecurity as a critical infrastructure concern

The EV charging ecosystem, comprising EVs, EVSEs, CPOs, system operators, and the grid, is a highly interconnected system that introduces a vast new cybersecurity attack surface. While issues of reliability and interoperability affect user convenience, a failure in cybersecurity could undermine the fundamental trust in the entire system. Vulnerabilities exist at every layer, from physical tampering with a charger to sophisticated denial-of-service attacks that could take down an entire charging infrastructure, or data breaches that expose sensitive user and financial information. A large-scale, coordinated cyberattack could even be used to destabilize the electrical grid by simultaneously manipulating the charging behaviour of thousands of vehicles. The perception of this risk alone can damage consumer confidence and slow EV adoption. Consequently, regulators are moving to embed cybersecurity into the system's design from the ground up. In Europe, the NIS2 Directive now officially classifies EV charging networks as critical infrastructure, subjecting them to stringent cybersecurity risk management and incident reporting requirements.

12. CONCLUSIONS

Deliverable 2.1 set out to capture the current capabilities and near-term evolution of electric vehicle charging technologies across road and maritime domains. By compiling field data, manufacturer specifications, pilot-project results and the latest regulatory texts, the study offers a coherent baseline against which future innovations can be measured. It highlights the technical strengths and weaknesses of each charging option, quantifies their impact on distribution grids, and situates European deployment within the wider global context.

12.1. Summary of Findings

The review confirms that single- and three-phase AC infrastructure remains the backbone of everyday charging because it leverages existing low-voltage networks and requires comparatively modest capital outlay; however, clustered 7–22 kW installations already produce local transformer overloads in dense districts, signalling the urgent need for smarter load-management. DC fast charging, now commonplace at 50–350 kW along highways and in logistics hubs, is advancing towards megawatt-scale systems that can refuel heavy-duty trucks and short-sea ferries within operationally acceptable dwell times, but the move to such power levels intensifies challenges related to grid-connection costs, power-quality compliance and thermal management. Commercial static wireless pads have reached around 90 % efficiency at 11 kW, providing a compelling hands-free alternative for taxis and shuttles, whereas dynamic in-road concepts remain pre-commercial. Bidirectional charging is technically proven—demonstrations show vehicles can deliver frequency regulation and backup power—yet widespread use is still hampered by immature market rules, cybersecurity concerns and the absence of standardized remuneration mechanisms. Across all modalities, the study finds that harmonized connector geometries, roaming protocols and cyber-secure communication stacks are prerequisite for cross-border interoperability and investment confidence.

12.2. Future Research Directions

Several knowledge gaps emerged that warrant targeted investigation. First, the thermal behaviour, cable ergonomics and electromagnetic-compatibility limits of megawatt-class DC systems require systematic laboratory and field trials, particularly for applications in articulated trucks and coastal vessels. Second, robust grid-integration models are needed to quantify the combined effect of high-power charging, distributed photovoltaics and vehicle-to-grid exports on feeder voltage stability, asset ageing and ancillary-service markets; such models should be validated with real-world data from diverse urban and rural networks. Third, improving wireless efficiency above 95 %, extending airgaps for larger ground clearances, and assessing long-term pavement durability for dynamic inductive lanes remain critical technical challenges. Fourth, automated conductive couplers and robotic connectors call for reliability testing under harsh environmental conditions and high utilization cycles typical of depots. Fifth, interdisciplinary work on cybersecurity, data governance and user privacy must keep pace with the deepening digitalization of charging ecosystems. Finally, socio-economic studies that capture driver behaviour, tariff responsiveness and equity impacts will be essential for designing business models that align stakeholder incentives with grid needs and climate targets. Addressing these research priorities will equip policymakers, network operators and technology developers with the evidence required to accelerate the deployment of resilient, interoperable and grid-friendly charging infrastructure across Europe’s road- and water-borne transport sectors.

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