D2.2

Innovative Grid Services for EVs

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EXECUTIVE SUMMARY

Deliverable *D2.2 Innovative Grid Services for EVs* establishes a comprehensive roadmap to transform the current charging infrastructure into a supporting asset for the electricity grid. The technical limitations of existing distribution grids are analyzed and translated into a systematic approach for designing next generation grid services tailored to electric vehicle (EV) charging.

The report begins with a two-level assessment of the power system constraints that influence the grid integration of EV charging infrastructure, at the distribution level, it quantifies distribution overload risks, voltage constraints. Moreover, at the transmission level, it assesses voltage stability margins, N–1 contingency criteria, and frequency constraints. Together, these findings establish the boundary conditions that any next-generation grid service must satisfy to preserve power quality and system reliability while enabling widespread and flexible EV charging. Building on this foundation, the report introduces several innovative grid services enabled by bidirectional V2X chargers highlighted as key enablers of flexibility, offering congestion management, capacity support, voltage stabilization, frequency regulation across distribution, transmission, and behind-the-meter contexts. Service concepts proposed within the AHEAD project demonstrators further illustrate how these solutions can be adapted to regional needs.

In parallel, the study reviews advance in converter topologies and semiconductor technologies that enhance the capability of EVs, HDEVs, and electrified vessels to interact dynamically with the grid. The role of standardized communication protocols is also examined, ensuring secure and interoperable integration, alongside the emerging concept of digital battery passports, which promote transparency, lifecycle traceability, and sustainability.

Overall, the findings underline that addressing technical constraints, deploying innovative grid services, and leveraging advanced technologies are all essential to enable electric mobility as a reliable contributor to future power system resilience.

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ACRONYMS

AC	Alternating Current
AC/DC	Alternating Current/Direct Current
AFE	Active Front-End
AMPC	Active Neutral-Point Clamped
API	Application Programming Interface
BESS	Battery Energy Storage System
BTM	Behind-the-Meter
CHAdeMO	Charge de Move (DC fast charging standard)
CLLC	Capacitor Resonant Converter
CMS	Charging Management System
CPMS	Central Point Management System
CPO	Charge Point Operator
DC	Direct Current
DER	Distributed Energy Resources
DSO	Distribution System Operator
EMS	Energy Management System
EN	European Norm
ENTSO-E	European Network of Transmission System Operators for Electricity
eMIP	eMobility Interoperation Protocol
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
G2V	Grid-to-Vehicle
GHG	Greenhouse Gas
HDV	Heavy-Duty Vehicle
HDEV	Heavy-Duty Electric Vehicle
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IEA	International Energy Agency
ISO	International Organization for Standardization
LV	Low Voltage
MMC	Modular Multilevel Converter
MQTT	Message Queuing Telemetry Transport
NERC	North American Electric Reliability Corporation

NPC	Neutral-Point Clamped Converter
OCA	Open Charge Alliance
OCHP	Open Clearing House Protocol
OCPP	Open Charge Point Protocol
OCPI	Open Charge Point Interface
OICP	Open InterCharge Protocol
Open ADR	Open Automated Demand Response
OSCP	Open Smart Charging Protocol
PFC	Power Factor Correction
PNNL	Pacific Northwest National Laboratory
PQ	Power Quality
PSFB	Phase-Shifted Full Bridge
PV	Photovoltaic
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
RoCoF	Rate of Change of Frequency
SCE	Southern California Edison
SG	Synchronous Generator
SME	Small and Medium-sized Enterprises
SoC	State of Charge
TAB	Triple Active Bridge
THD	Total Harmonic Distortion
TSO	Transmission System Operator
V1G	Controlled Unidirectional Smart Charging
V2B	Vehicle-to-Building
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
V2L	Vehicle-to-Load
V2X	Vehicle-to-Everything
VSM	Voltage Stability Margin
WPT	Wireless Power Transfer

1 INTRODUCTION

The accelerating electrification of road transport is reshaping the power system planning horizons, since global electric vehicles (EVs) sales neared 17 million in 2024, or almost one in every five cars sol is an EVs, and the International Energy Agency (IEA) projects that public Electric Vehicles Supply Equipment (EVSE) will rise four-fold from 2020 to over 15 million by 2030 [1]. While aggregate energy demand remains modest, ENTSO-E estimates that even the full roll-out of Heavy-Duty Electric Vehicles (HDEVs) would account for approximately 3 % of Europe's electricity consumption in 2030, the power drawn by fast and depot EVSEs is highly concentrated in space and time, creating new operational bottlenecks [2]. At the distribution level, simultaneous high-power charging can push feeders beyond their thermal ratings, induce voltage excursions, aggravate phase imbalance and overload legacy protection schemes; recent studies show that these impacts are often an order of magnitude larger than the underlying energy increment, making smart-charging orchestration a prerequisite for cost-effective integration [3].

To mitigate these constraints, vehicle-to-everything (V2X)-enabled charging infrastructure is emerging as a cornerstone of grid flexibility, offering services such as capacity support, congestion management, and voltage stabilization [4]. These capabilities are enhanced by advanced power electronics in EVs, HDEVs, and maritime vessels, allowing more dynamic interaction with the grid [4]. In the maritime sector, the development of electric propulsion, especially in short-route ferries, has accelerated this trend. Recent deployments of fully electric ferries with high-capacity batteries and fast-charging systems demonstrate how maritime vessels can support low-emission operation and enable efficient shore-to-ship power exchange [5]. Standardized communication protocols ensure secure, interoperable control [5], while digital battery passports promote traceability and sustainable integration [6]. These innovations are shaping the future of research at the nexus of transport electrification and power grid resilience.

The objective of this work is to provide a structured assessment of both the technical constraints and the enabling solutions for large-scale integration of charging infrastructure. Section 2 analyses distribution and transmission system limitations, including overload, voltage, and frequency challenges. Section 0 explores innovative grid services enabled by V2X chargers, addressing constraints across distribution, transmission, and behind-the-meter contexts, while also presenting service concepts designed for the regional demonstrators of the AHEAD project. Section 0 reviews advanced converter topologies and semiconductor technologies that strengthen the ability of EVs, HDEVs, and electrified vessels to support the grid. Section 5 discusses communication protocols and the emerging role of battery passports for interoperability and sustainable integration. Finally, Section 6 concludes with overarching findings and recommendations.

2 TECHNICAL CONSTRAINTS FOR GRID INTEGRATION OF CHARGING INFRASTRUCTURE

The integration of EV charging infrastructure into existing power grids presents several technical constraints that must be carefully addressed to ensure reliable, efficient, and safe operation. As EV adoption continues to increase, electricity grids, typically designed for more predictable and less dynamic loads, are being challenged by rapidly changing load profiles associated with EV charging [7]. These load variations are often concentrated in relatively short periods of time, for example during peak commuting hours and the volatile generation like solar and wind in the distribution grid, increasing the risk of localized grid congestion and voltage instability. A considerable issue in this context is related with the transformer and feeders' capacity, since some of them were probably not dimensioned to accommodate the high demand for electricity usage in general, heat pumps and, of electric mobility.

2.1 Distribution system power constraints

2.1.1 Distribution overload

Distribution overloads take place when the electrical current in a component, like a power line or transformer, exceeds its thermal rating, or when power demand surpasses the operational limits of the grid, this condition can be either temporary or sustained [8]. From a network access perspective, an overload means the system lacks the capacity for new connections, thereby constraining expansion [8]. The definition of overload is evolving from a static concept based on fixed limits to a dynamic, probabilistic one. The integration of variable renewables and fluctuating loads such as EVs drives this shift.

The prospect of millions of EVs plugging into low-voltage grids turns distribution overload from a sporadic reliability concern into a systematic planning and operational problem. Large-scale empirical work using feeder-level metering in California shows that uncoordinated charging can double peak demand and push more than 20% of service transformers beyond their nameplate ratings during evening hours [9].

From the e-mobility charging infrastructure point of view, several concerns are detailed below:

- **Thermal overloading of distribution transformers and low-voltage (LV) feeder cables:** Uncoordinated charging, particularly the simultaneous connection of multiple high-power fast EVSEs, can lead to current flows that exceed the rated capacity of these components. Studies based on real-life driving patterns and electricity network data indicate that a significant number of LV transformers and a substantial portion of LV feeder cables could become overloaded if no charge control measures are implemented. An additional challenge is the real-time operation, it is necessary to observe, have the correct grid model, compare measurements with physical limits and thereafter know which assets are available to contribute to correct the observed overload.
- **Increased system losses:** EVs are highly dependent on factors such as the existing grid topology (radial vs. meshed, conductor sizes, transformer capacities), the geographical concentration of EVs, the power levels of EVSEs (Level 2 vs. DC fast charging), and the temporal patterns of charging behaviour (e.g., simultaneity of charging during evening peaks) [13]. This inherent variability means that certain parts of a distribution network, often referred to as "weak links", will experience adverse effects much sooner and more severely than others. For example, studies like the one on the SCE Mallet feeder demonstrated that specific secondary transformers were prone to overloading based on the circuit's characteristics and projected EV adoption patterns [14].

2.1.2 Voltage Constraints

The fundamental need to regulate voltage within specified limits arises from considerations of safety, power quality, and the efficient operation of both utility equipment and consumer appliances. Deviations from prescribed voltage levels can lead to a cascade of undesirable consequences, including equipment malfunction or premature failure, increased energy losses within the power system, and, in severe cases, broader system instability. The major blackout across the Iberian Peninsula on 28 April 2025 [13], triggered by a sudden voltage surge and cascading grid failures in Spain, exemplifies how even transient voltage deviations can precipitate large-scale outages. Voltage constraints, therefore, represent the permissible operational boundaries for voltage magnitudes at various nodes or buses throughout the distribution system.

A significant transformation is underway as traditional, passive distribution networks, designed for one-way power flow, are increasingly evolving into active networks. This shift is largely driven by the integration of Distributed Energy Resources (DERs), such as solar photovoltaic (PV) systems and wind turbines, at the distribution level [16]. These resources introduce bidirectional power flows, as power can now be injected into the grid at various points along the feeders [17]. Consequently, the challenge of managing voltage constraints is no longer solely focused on mitigating voltage drop along feeders but also, and increasingly, on preventing overvoltage conditions, especially in areas with high DER penetration.

Compounding this complexity is the trend towards the "electrification of everything," which encompasses the growing adoption of EVs and other significant electrical loads. This trend places a dual pressure on distribution networks [18]. On one hand, networks must accommodate increased overall loading, which can be highly variable, as exemplified by the concentrated demand from EVSEs [19]. On the other hand, they must simultaneously integrate intermittent and often non-dispatchable generation from DERs. The confluence of these factors, higher, more volatile demand and variable, localized generation, creates an exceptionally dynamic voltage profile.

As noted, EVs represent an extra and increasing load for the power system. This additional load, especially if it is uncoordinated and coincides with existing residential or commercial peak demand periods, can significantly exacerbate these peaks [20]. This may lead to substantial voltage fluctuations across low-voltage feeders, particularly at the end of distribution lines where voltage drops are more pronounced. Such effects can cause voltage deviations beyond regulatory limits. One of the most immediate and widely reported consequences of increased EV charging load is the distortion of the network voltage profile, detailed as follows:

- **Voltage Drop:** The increased current drawn by EVSEs flowing through the impedance of distribution lines and transformers inevitably leads to voltage drops. This effect is typically more pronounced at nodes electrically distant from the substation or on feeders that are already heavily loaded. Research indicates that "voltage issues in overloaded grids are possible, particularly when peak demands coincide with EV charging times". Numerous studies have confirmed that EV integration can lead to voltage levels falling below the lower permissible limits, constituting voltage violations. The authors in [19], [20], [21] collectively show that uncoordinated EV charging causes voltage drops and transformer stress, making voltage violations a key limitation for EV hosting capacity and highlighting the need for coordinated charging and voltage-control measures.
- **Voltage Fluctuations:** The charging process for EVs is not always constant or predictable. Variables such as the initial State of Charge (SoC) of the battery, the charging rate selected (which can sometimes vary during a session), the battery capacity, and the often-random arrival and departure times of EVs at EVSEs contribute

to a dynamic and fluctuating load profile. These load variations can, in turn, lead to increased voltage fluctuations on the network, potentially degrading power quality and affecting sensitive equipment [21]. While bidirectional charging (V2G) is proposed as a solution to mitigate such fluctuations, uncontrolled charging remains a concern.

- **Voltage Unbalance:** A significant portion of EV charging, particularly residential Level 1 and Level 2 charging, occurs using single-phase connections. If a disproportionate number of EVs are connected to and charging from the same phase in a three-phase distribution system, it can lead to an uneven distribution of load across the phases. This results in voltage unbalance, where the voltage magnitudes of the three phases differ significantly. It has been highlighted that "If the uncoordinated charging of EVs occurs, then voltage unbalance will cross the allowable limit" [22]. Severe voltage unbalance can cause negative sequence currents, leading to overheating in three-phase motors, increased losses in transformers and lines, and potentially excessive currents in the neutral conductor, which can also lead to overheating and safety hazards.
- **Nodal voltage violations:** High power demand from EVSEs can cause voltage levels at various nodes along a feeder, especially those electrically distant from the substation, to drop below statutorily permissible limits (e.g., below 0.95 per unit). Such under-voltages can impair the performance of other connected consumer appliances and industrial equipment.

The influence of EV penetration levels also can impact the voltage levels in the power system. There is a direct correlation between the level of EV penetration and the severity of grid impacts [19]. Multiple studies suggest that many existing distribution grids can accommodate EV penetration levels of around 20–30% without encountering widespread, severe issues, although this threshold is highly dependent on the specific characteristics and existing loading of the grid in question. Weaker grids or those already heavily loaded may experience problems at lower penetration levels [18]. On the other hand, uncoordinated ("Dumb") Charging, in which EVs begin charging immediately upon being plugged in, typically at maximum power, without regard for grid conditions or electricity prices. If many EV owners plug in their vehicles upon returning home in the evening, this uncoordinated charging often coincides with existing residential peak demand, creating the most significant stress on the grid in terms of voltage drops and equipment loading [23]. It has been observed that uncontrolled EV charging can exacerbate voltage variations, whereas controlled or "smart" charging can mitigate these issues.

Table 1 – Distribution system power constraints and E-Mobility impacts.

Distribution constraints	Key issues	E-mobility impact
Distribution overload	• Current exceeds thermal rating of lines/transformers • Limited hosting capacity for new connections • Shift from static to probabilistic overload definition	• Thermal overloading of LV transformers and feeder cables due to uncoordinated charging • Nodal voltage violations • Phase unbalance from single-phase EVSEs • Increase losses in weak lines
Voltage constraints	• Need to maintain voltage within statutory limits (≈0.95 – 1.05 pu) • Traditionally focused on undervoltage; now also overvoltage due to DERs • Dynamic voltage profiles from load growth + DER variability	• Voltage drops at distant nodes • Voltage fluctuations due to stochastic charging behaviour (SoC, arrival/departure, charging rates) • Voltage unbalance from single-phase connections

2.2 Transmission system power constraints

2.2.1 Voltage instability

Voltage stability is formally defined as the ability of a power system to maintain steady, acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance. It is fundamentally a problem of load stability, concerned with the ability of the generation and transmission system to serve the load. A system is considered voltage stable if voltages approach a steady-state value following a disturbance [28]. Conversely, voltage instability occurs when a disturbance—such as a sudden increase in load demand, changes in system conditions (e.g., a transmission line outage), or voltage oscillations arising from poor interoperability between power electronic converters, leads to a progressive and uncontrollable decline in voltage. The ultimate and most severe outcome of this instability is voltage collapse; this is the process by which the sequence of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant part of the power system [28]. To quantify the system's proximity to this critical state, system planners and operators rely on several key metrics:

- **Voltage Stability Margin (VSM):** This is the difference, typically measured in volts or per-unit (p.u.), between the current operating voltage at a bus and the voltage at the critical point of collapse. It serves as a direct measure of how close or far the system is from voltage failure under the prevalent operating conditions [28].

- **Loadability Margin:** This metric quantifies the amount of additional load, expressed in megawatts (MW) or megavolt-amperes reactive (MVAr), that the system can sustain at a specific bus or within a region before reaching the point of voltage instability. It is often visualized as the distance from the current operating point to the "nose" or maximum power transfer point of a Power-Voltage (P-V) curve [28].

Voltage instability occurs across different timescales, each driven by the response speeds of specific system components, requiring tailored analysis and mitigation approaches. long-term voltage instability develops over several seconds to minutes. Short-term voltage instability arises within seconds after major disturbances. Very short-term/converter-driven instability occurs within sub-seconds to a few seconds. These fast control-related instabilities stem from power electronic converters, leading to voltage oscillations that challenge control system stability rather than power delivery. The addition of a large EV charging fleet directly impacts the core metrics of voltage stability by increasing the system's reactive power demand and altering its response to disturbances.

2.2.2 N–1 Contingency Constraints

For decades, the reliable operation of transmission systems has been anchored by a foundational principle: the N–1 security criterion, that mandates that the power grid must be planned and operated to withstand the sudden, unexpected loss of any single major component, such as a transmission line, generator, or transformer, without violating system operating limits, destabilizing the system, or causing a cascading failure that leads to widespread outages [29]. The N–1 criterion is the bedrock of grid resilience, a defensive pre-configuration designed to ensure continuity of service in a system where the speed of a fault often precludes real-time human intervention. It is a core tenet of grid codes and reliability standards enforced by organizations like the North American Electric Reliability Corporation (NERC) and is a central function of the Energy Management Systems (EMS) used by grid operators for both long-term planning and real-time operational security [30].

The integration of EVs brings not just higher electricity demand but a new type of load with distinct characteristics that create significant stresses across all grid levels. EV proliferation reshapes load profiles, challenges equipment limits, affects power quality, and transforms grid operation and planning [31]. The integration of millions of EVs creates a new operational reality for power systems, one where the foundational N–1 security criterion is tested in novel and complex ways. The core of the challenge lies at the intersection of the new, demanding EV load profiles and the established principles of contingency analysis. High EV penetration does not merely add load; it actively reduces operational margins, alters the nature and severity of contingencies [29]. Moreover, common protection settings for many similar devices may also be a concern, reference to Spanish blackout where overvoltage protection setting for solar generation added to the challenge [13].

The most direct impact of EV charging on N–1 security is the reduction of operational headroom. In a pre-EV world, transmission lines and transformers are typically operated well below their maximum thermal ratings to provide a buffer. This spare capacity is essential to accommodate the rerouted power flows that occur following a contingency. When a large EV charging load is added to the system, particularly during peak hours, it consumes a significant portion of this buffer. The baseline, pre-contingency loading on all system components increases [32]. Consequently, when an N–1 event occurs, for instance, the loss of a major transmission line, the remaining parallel paths in the network are forced to carry a much larger share of the rerouted power. Because these lines are already operating closer to their limits, they are far more likely to become thermally overloaded, triggering further protective actions and potentially initiating a cascading failure. The system's resilience is compromised because its capacity to absorb the shock of a contingency has been pre-emptively consumed by the EV load.

2.2.3 Frequency Constraints

Frequency serves as a real-time indicator of the equilibrium between electricity generation and demand across the entire interconnected system. Deviations from the nominal frequency signify an imbalance that, if not corrected promptly, can lead to widespread disruptions [33]. Grid frequency stability is essential for the reliable operation of power systems, reflecting the real-time balance between electricity generation and demand. Typically maintained around 50 or 60 Hz, frequency serves as a key indicator of system equilibrium. Any divergence between active power generation and consumption results in a frequency deviation. If generation exceeds demand, the surplus energy accelerates the rotating masses of synchronous generators, causing the frequency to rise. Conversely, if demand surpasses generation, the deficit in energy causes generators to decelerate, leading to a frequency drop.

The widespread, uncoordinated charging of EVs can have a range of detrimental impacts on the power system, such as, Frequency Fluctuations: The sudden, large increase in aggregate load caused by simultaneous, uncoordinated charging directly leads to a drop in the system frequency. The inherent volatility of this demand can induce rapid frequency fluctuations that tax the grid's regulation capacity and can weaken the system's overall ability to withstand other contingencies.

Table 2 – Transmission system power constraints and E-Mobility impacts.

Transmission constraints	Key issues	E-mobility impact
Voltage stability	• Defined as inability to maintain acceptable bus voltages after a disturbance • Progressive decline may lead to voltage collapse and blackouts • Occurs over multiple timescales: long-term (seconds–minutes), short-term (seconds), and very short-term (converter-driven, sub-seconds)	• EV charging fleets increase reactive power demand • Alter system response to disturbances • High penetration exacerbates converter-driven fast instabilities
Contingency constraints	• Grid must withstand loss of any single major component (line, generator, transformer) without cascading failures • Principle codified in grid codes and EMS operations (e.g., NERC standards) • Ensures reliability by maintaining operational “headroom”	• High EV load reduces operational margins and headroom • Increases baseline loading of lines/transformers • Following a contingency, parallel paths more likely to overload, higher cascading failure risk
Frequency constraints	• Frequency reflects instantaneous balance of generation vs. demand (Hz) • Deviations arise when demand ≠ generation • Conventional stability relies on synchronous generator inertia	• Uncoordinated EV charging causes sudden large load increments • Leads to rapid frequency drops and fluctuations • Increased volatility challenges regulation reserves and weakens ability to handle contingencies

3 INNOVATIVE GRID SERVICES FOR V2X CHARGER

V2X charging and smart charging are two ways that EVs can provide valuable services to the grid. V2X charging, which allows for bidirectional power flow, enables EVs to act as flexible energy resources at the residential, community, and grid levels [34], [35]. This can help reduce energy costs, provide backup power during outages, and support grid stability by helping with peak shaving, load shifting, and frequency regulation.

Smart charging, which is a controlled unidirectional charging strategy, also provides benefits even without bidirectional power flow. Combining both approaches expands the potential services available to end-users and grid operators, which can help avoid expensive infrastructure upgrades and integrate renewable energy sources more effectively.

This section describes a series of innovative grid services that use these capabilities to address challenges in the electrical system. These services are categorized into three groups: solutions for distribution systems, solutions for transmission systems, and services for behind-the-meter needs. Each service is detailed by its name, description, contract type, activation actor, e.g., Distribution System Operator (DSO), Transmission System Operator (TSO), or an aggregator, and setpoint definition (e.g., power limit, price signal), activation mechanism, and whether it uses V2X, smart charging, or both, including the technical characteristics of the EVSE to allow the service implementation. Moreover, the innovative grid services are grouped into the mode, i.e., it is based on price signals, direct control, regulatory aspects, and ancillary services.

3.1 Innovative grid services for Distribution System challenges

3.1.1 Grid services based on price signals

- **Congestion Management:** This grid service mitigates distribution-level overloads by coordinating EV charging and, where available, discharging. The service is implemented triggering events when real-time or forecasted loading indicates congestion. Delivery is constrained by EVSE and installation technical capabilities, via an energy management system that issue power setpoints that the EVSE enforces locally using smart-charging profiles supported by OCPP 1.6/2.0.1, respecting connector nameplate limits, minimum controllable power, and phase availability/switching. Setpoints are transmitted automatically via a secure Application Programming Interface (API) and translated to EVSE/vehicle commands; if communications drop, the EVSE falls back to a safe local profile while preserving user SoC and departure constraints. Control modes include V1G, throttling, pausing, or shifting unidirectional charging to fit network capacity, and V2G, when supported by the EV/EVSE (e.g., ISO 15118 features, bidirectional power limits, grid-code protections), enabling controlled export during peaks with guaranteed make-up charging afterward. End-user preferences (minimum SoC, latest departure, price caps, battery health) and instant override are honoured.

- **Voltage Control in LV Grid:** This service maintains voltage limits in LV distribution networks by modulating EV power at the EVSE, either reducing import (V1G) or exporting power (V2X) when technically available. It can run under a bilateral DSO and service provider contract with price-based indexed to local voltage margins: near the lower limit, high prices discourage charging and incentivize discharging; near the upper limit, low prices encourage charging and discourage discharging. The service is thus implemented through dynamic price signals that already internalize voltage-support needs. Users simply follow these price variations, and their collective charging or discharging behaviour naturally delivers the intended voltage regulation effect. Delivery explicitly respects EVSE and site capabilities: EVSE must support control (e.g., OCPP 1.6/2.0.1 smart charging profiles), enforce nameplate and site limit, minimum controllable power, ramp-rates, and per-phase constraints; V2X requires compatible EV/EVSE (e.g., ISO 15118-2/-20) and certified bidirectional limits. User constraints (minimum SoC, latest departure, battery health) and instant override are thrilled, with make-up charging scheduled to restore the target SoC after an event.

3.1.2 Grid services based on direct control

- **Phase Balancing:** This grid service targets phase balancing in low-voltage networks where single-phase electrical systems are unevenly distributed across the three phases of a three-phase supply. It is implemented under a bilateral agreement between the distribution system operator (DSO) and the service provider, potentially complemented by market-based incentives. The service is activated by a signal from the DSO or an aggregator that determines control actions based on real-time per-phase voltage measurements. Via direct control, the phase tending toward imbalance is discouraged from further charging, while lighter phases are managed to attract additional load within admissible power limits. Although EVSEs provide per-phase telemetry (voltage, current, and status), the actual control is applied at the connector level, meaning identical current is typically set across all phases. Smart-charging protocols such as OCPP 1.6 and 2.0.1 enable these coordinated adjustments, ensuring compliance with connector ratings, minimum controllable current, and site-level load-balancing constraints.

- **Peak Shaving:** This service manages EV charging at the EVSE to shave demand peaks and optimize local load profiles. It operates under a bilateral contract between the DSO and an aggregator and can be activated proactively based on forecasts or real-time load conditions indicating approaching peak periods. Operationally, it falls under direct control: once an activation signal is received (maximum power limit in the installation), the commanded setpoint is enforced at the EVSE, immediately reducing, or, if necessary, cutting, charging power. Control is expressed as per-EVSE (or per-feeder) power setpoints, absolute W, that the EVSE must enforce locally. Delivery explicitly respects charger/site characteristics: EVSE supporting smart charging (e.g., OCPP 1.6/2.0.1) apply limits within connector nameplate ratings and minimum controllable power, site constraints and main-breaker limits are observed via load balancing across connectors. Setpoints are dispatched either through the site energy management system or directly from the DSO/aggregator via a secure API (WebSocket/MQTT) for faster, coordinated actions; revenue-grade metering and live telemetry (P, V, E, status) back settlement and compliance.
- **Direct Load Management with DSO inputs:** This service adjusts EV charging in real time according to the loading of distribution assets, operating under a bilateral DSO and a service provider contract. The DSO, working with the Charging Point Operator (CPO) and the Charging Point Management System (CPMS), acts as the activation actor and issues dynamic power setpoints that track feeder and transformer conditions; these are enforced at the EVSE to immediately throttle or, if needed, pause charging. Delivery explicitly respects EVSE and site capabilities: EVSE that support smart charging via OCPP 1.6 apply absolute or relative limits within connector nameplate ratings, minimum controllable current as per IEC 61851, and site limits through local load balancing. Setpoints are carried over secure APIs such as WebSocket or MQTT and translated into EVSE commands; revenue-grade metering and live telemetry of power, voltage, energy, and status enable verification and settlement. If communications fail, a fail-safe local profile is applied, and user constraints are preserved. User preferences such as minimum SoC, latest departure time, battery health bounds, and instant override are always guaranteed, with make-up charging scheduled as required. Operation is V1G, using unidirectional smart charging to align demand with available grid capacity while meeting driver requirements.

3.1.3 Grid services based on Regulatory Framework

- **Conditional Connection Agreement:** This service dynamically adjusts EV charging rates in real time according to the loading conditions of distribution assets, operating under regulatory supervision and in compliance with DSO-defined technical requirements. The DSO, working with the CPO or charging point management system, acts as the activation actor and issues dynamic power setpoints that track feeder or transformer conditions; these are enforced at the EVSE to immediately throttle, or, if necessary, pause charging. Delivery explicitly respects charger and site capabilities: EVSE supporting smart charging (e.g., OCPP 1.6/2.0.1) apply absolute or relative limits within connector nameplate ratings, minimum controllable power, ramp-rate constraints, per-phase availability, and main-breaker limits via local load balancing. Setpoints are conveyed over secure APIs (WebSocket/MQTT) and translated into EVSE commands; revenue-grade metering and live telemetry (P, V, E, status) enable verification and settlement. Fail-safe local profiles apply on communications loss, and user constraints (minimum SoC, latest departure, battery-health bounds, instant override) are privileged with make-up charging scheduled as needed. Operation is V1G (unidirectional), aligning demand with available grid capacity while preserving driver requirements.

- **Voltage Control:** This grid service operates within the regulatory framework governing voltage quality in LV networks, aiming to prevent voltage sags by modulating EVSE power in response to real-time voltage measurements. It functions under a defined DSO, aggregator arrangement that specifies operational roles, performance criteria, and compliance verification. The activating entity, either the DSO or the aggregator, derives dynamic setpoints based on regulated voltage bands and instantaneous phase measurements, then applies per-EVSE control signals enforced locally. Service delivery adheres to charger and site capabilities: EVSEs supporting smart charging via OCPP 1.6 or 2.0.1 implement absolute or relative power limits consistent with connector nameplate ratings, minimum controllable current per IEC 61851 for AC interfaces, ramp-rate limits, phase availability, and site load-balancing constraints. When voltage approaches the lower permissible band, charging is throttled or suspended; as voltage recovers, power is gradually restored while make-up charging is scheduled to ensure the driver's target SoC is achieved before departure. Continuous telemetry, voltage, current, power, energy, and status, together with revenue-grade metering ensures traceability and regulatory compliance. Setpoints and measurements are exchanged via secure APIs (e.g., WebSocket or MQTT) with the site EMS or CPMS, while fail-safe local profiles maintain protection during communication loss, always safeguarding user conditions such as minimum SoC, latest departure time, battery health, and immediate override capability.

3.2 Innovative grid services for Transmission System challenges

- **Frequency Droop Control:** This service delivers fast frequency support by modulating EV power at the EVSE in real time. Implementation is constrained by EVSE and vehicle capabilities: V1G EVSE adjust import within connector nameplate ratings and minimum controllable current, while V2G pairs require certified bidirectional power limits, DC link, thermal protections, and battery SoC. The control law is a frequency droop with a small deadband around nominal, defined setpoints for maximum up and down regulation, and a verified response time. Setpoints may be issued under a bilateral contract with the TSO via an aggregator and are enforced by the EVSE using smart charging profiles or converter P and Q references. The EVSE or site controller measures frequency with adequate resolution and filtering, applies priority rules and SoC safeguards, and automatically reduces charging or initiates discharging when thresholds are crossed, then restores power and schedules make-up charging to meet the driver target SoC by departure.
- **Black Start Support for Power System**: This service enables EVs to assist in restoring power to the system following a blackout by providing controlled energy injection. It operates under a bilateral contract between the aggregator and the system operator, defining technical requirements and operational procedures. The activation actor is the local TSO, who triggers the service when a black start is required. The setpoint definition specifies a power limit per vehicle, ensuring coordinated contributions that match the system's restoration capacity. The activation mechanism is managed through the local EMS, when a black start is required, the TSO operator arms the sequence via the local EMS. Hence, throughout, the EMS enforces SoC reserves, droop setpoints, and ramp constraints to keep voltage/frequency within bounds, while telemetry from each charger (P/Q, SoC, temperatures, breaker status) closes the control loop. In practice, participating EVSE must be V2G capable with fast active power control, while requiring SoC operating windows and communication protocols such as OCPP 1.6/2.0.1.
- **Inertia Emulation:** this service can enhance system stability in power system by replicating the inertial response of synchronous generators through power electronics and control algorithms. It is implemented as a regulatory obligation, ensuring

compliance with stability requirements. The activation actor is the TSO, which monitors system conditions and compares them against a setpoint definition based on local inertia thresholds. When these thresholds are approached, the system reacts by injecting or absorbing power to counteract frequency variations. The activation mechanism uses data from local inverter sensors to trigger rapid adjustments. The EVSE must be V2G capable with sufficient power rating and short response times. A hierarchical control scheme is used in which the EVSE's inner loops execute setpoint changes from local frequency measurements, while a supervisory controller compares operating conditions to predefined "virtual inertia" thresholds that account for SoC limits and EVSE compliance (OCPP 1.6/2.0.1).

- **Renewables Curtailment Mitigation:** This service, with EV charging service, can reduce renewable energy curtailment by directing surplus generation to EV charging. It is established under a flexibility contract with the TSO or an aggregator, ensuring that renewable integration is prioritised within market or operational frameworks. The activation actor is the TSO, who identifies renewable energy surpluses and triggers additional charging demand to absorb excess generation. The setpoint definition corresponds to the level of RES surplus (W), with charging adjusted dynamically to maximise renewable utilisation. The activation mechanism is automated, based on signals from the TSO, allowing rapid alignment of EV charging demand with renewable generation availability. EVSE must support dynamic per connector power control and scheduling (OCPP 1.6J/2.0.1 or ISO 15118-20), respect AC IEC 61851 and DC CCS limits

- **EV charging curtailment:** this service is proposed to reduce charging demand to support system stability when unexpected grid events occur, such as N–1 contingency. It is defined as a grid code requirement, ensuring that EV charging infrastructure contributes to maintaining security of supply under stressed conditions. The activation actor can be TSO, who triggers the service when contingency events, such as generation outages or network failures, are detected. The setpoint definition is based on a power limit, restricting charging load to a specified threshold to relieve stress on the system. The activation mechanism is managed through the TSO's contingency dispatch platform, which issues signals directly to charging infrastructure for immediate and coordinated response. EVSE must support communications protocols that must be secure and low latency, such as OCPP 1.6J/2.0.1.

- **Reactive Power Support:** To solve N–1 contingency constraints, this service is proposed to provide voltage regulation capabilities by using EV fleets to supply or absorb reactive power. This service can be implemented under either a market-based contract or a regulatory obligation, depending on the system operator's framework. The activation actor is the TSO, who defines the operational requirements and triggers the service. The setpoint definition is based on voltage thresholds, ensuring that reactive power is dispatched when the grid voltage deviates from acceptable limits. The activation mechanism is enabled via an API connection from the TSO to the aggregator or directly to the inverter, allowing fast and reliable adjustments. Moreover, It is necessary to coordinate the response with the local DSO to avoid any regulation that may be harmful in the DSO grid. This service relies on V2G functionality, enabling bidirectional power flows that strengthen grid stability and enhance overall system reliability. EVSE must secure control and telemetry (OCPP 2.0.1), and compliance with ride through and power quality standards (EN 50160/IEEE 519). DC off-board V2G should provide Q at P≈0 (AC on-board depends on vehicle and ISO 15118/IEC 61851), and a local Volt–VAR fallback must sustain autonomous support if communications fail.

- **Frequency Adaptation:** this service is planned to enable EVs to contribute to system stability by adjusting their charging behaviour in response to frequency deviations. It is implemented under a contractual agreement or markets, which defines the operational conditions for participation. The activation actor is the TSO, who oversees service activation based on system needs. The setpoint definition is linked to predefined frequency thresholds, which trigger automatic adjustments to charging power levels. The activation mechanism can rely on digital communication channels such as WebSocket or MQTT broker, ensuring real-time responsiveness. This service can be delivered through V1G operation, applying unidirectional smart charging control to support frequency stability without requiring bidirectional energy flows. EVSE must support communications protocols that must be secure and low latency, such as OCPP 1.6J/2.0.1.
- **Fast Frequency Response:** Proposed for EV Fleets, this service can provide rapid stabilisation of grid frequency by utilising the aggregated flexibility of EV fleets. It operates under market-based ancillary service contracts, which define the commercial terms for participation. The activation actor can be either the TSO or an aggregator, depending on the market structure and operational framework. The setpoint definition is based on predefined frequency thresholds, which trigger immediate adjustments in charging or discharging power. The activation mechanism relies on real-time frequency measurements combined with API-based communication, ensuring fast and

coordinated response across multiple EVs. EVSE must support secure, low-latency communication protocols such as OCPP 1.6J/2.0.1. For instance, in the Nordic FFR market, activation is triggered directly by local frequency measurement, as the response requirements of 0.7–1.3 s leave insufficient time for remote communication. Asset arming for threshold frequencies between 49.7–49.5 Hz may occur via TSO communication or according to a predefined control plan.

- **Frequency Regulation Services:** This service can allow EVs to participate in frequency control either through V2G discharging or V1G load reduction, as already implemented in markets such as DK2 (Denmark). It is delivered under a market-based contract, enabling competitive participation of EV fleets in ancillary service markets. The activation actors include the TSO, balancing service providers, or balance responsible parties, who dispatch the service when grid frequency deviates from the nominal value. The setpoint definition is a frequency command, with charging or discharging automatically adjusted to counteract imbalances. The activation mechanism is fully automatic, ensuring rapid response to frequency events and contributing to overall system stability. EVSE must support communications protocols that must be secure and low latency, such as OCPP 1.6J/2.0.1.

3.3 Innovative grid services for Behind the Meter challenges

While distribution and transmission level grid services primarily address system wide stability, congestion management, and reliability, Behind-The-Meter (BTM) services operate at the consumer or building level, offering local flexibility that can complement broader system needs. By leveraging controllable loads, smart charging, V2X EVSEs, and home or building energy management systems, BTM services enable end-users to actively contribute to grid stability while optimising their own energy use and costs [36]. These services provide a bottom-up approach to flexibility, supporting distribution and transmission operators indirectly, while being directly implemented through local contracts and energy management strategies.

3.3.1 Local Load Management

The Local Load Management for EVSE service is proposed to allow building-level energy management systems to automatically adjust charging rates based on local grid capacity and total site demand. This service is implemented under a contractual agreement, typically between the building owner or facility operator and the service provider or aggregator. The activation actor can be the building manager, who oversees the operation and ensures that flexibility commitments are respected. The setpoint definition is based on a power limit (kW), ensuring that the aggregated demand of EVSEs and other flexible loads does not exceed predefined thresholds (contracted power of the installation). The activation mechanism relies on local measurements, typically obtained from smart meters, which provide real-time consumption data to the energy management system that affectively control the EVSE via communication protocols. This enables dynamic adjustment of charging rates and other controllable loads, ensuring compliance with limits while maintaining end-user comfort and optimising energy costs.

3.3.2 Demand Response

The Demand Response Participation service can enable BTM assets, such as EVs or other flexible loads, to respond to market signals and contribute to system balancing. It is implemented through a market-based mechanism, where participants are incentivised to adjust their consumption in response to electricity price variations or flexibility requests. The activation actor can be the aggregator, who coordinates multiple consumers and communicates control instructions. The setpoint definition is based on a price signal, which determines when and how demand should be shifted or reduced. The activation mechanism operates via an API connection from the aggregator, allowing real-time participation in demand response programs while ensuring consumer benefits and system-level support.

3.3.3 Fair and Smart EVSE scheduling

With fewer EVSEs than households, an EMS allocates charging slots by need and availability to ensure fairness and avoid peaks. This BTM services is proposed to coordinate access and power sharing when EVSEs are scarce, scheduling time slots and per vehicle setpoints so total site demand remains within limits. The service is implemented under a contractual agreement between the building owner/house owner and a service provider or aggregator, defining booking windows and priority rules (e.g., accessibility or emergency users). The activation actor is the building manager (or designated EMS operator), who oversees operation and ensures that fairness policies and flexibility commitments are respected. The setpoint definition is in W with user energy derived from declared departure times and target SoC; fairness can follow earliest departure first with SoC tie breaks, rotating priority tiers, or pro rata sharing. The activation mechanism relies on local measurements (smart meter and EVSE telemetry) and the mobile app: users declare arrival/departure and energy needs; the EMS computes a schedule that limits simultaneous sessions, balances phases, adapts to ToU tariffs, and updates in real time as EVs plug/unplug; commands are sent to EVSE via standard protocols (e.g., OCPP 1.6/2.0.1, smart charging). This enables dynamic adjustment of slot assignments and charging rates, preserves contractual demand limits, minimizes scheduling times and peaks, and maintains user comfort with clear notifications and graceful fallbacks during communications loss

3.3.4 Dynamic Tariff and Flex Management

The BTM responsive BESS and EV dispatch service is proposed to coordinate stationary Battery Energy Storage System (BESS) and EV charging/discharging in response to tariff signals, minimizing bills and reducing dependence on the main grid. The service is implemented under a contractual agreement between the building owner and a service provider, aggregator, or retailer, defining data access, settlement, and user consent. The activation actor is the building manager (or EMS operator), who oversees operation and ensures that flexibility commitments are respected. The setpoint definition combines a power signal in W aligned with price signals, PV forecasts, and contracted capacity. The activation mechanism relies on local measurements from smart meters, BESS, and EVSE telemetry; the EMS computes and updates charge/discharge schedules in real time and issues commands via standard protocols (e.g., Modbus/IEC 61850 for BESS; OCPP 1.6/2.0.1 or ISO 15118 for EVSE). This enables peak shaving, load shifting, and PV self-consumption without breaching limits, while respecting user departure times and restoring normal schedules when price events end.

3.3.5 Self-consumption in house or building

This BTM service is proposed to use locally produced PV energy, optionally buffered in a BESS or an EV (V2H/V2B), to supply the building's own loads and reduce grid imports. The service is implemented under a contractual agreement between the building owner and a service provider or aggregator, defining data access, settlement, and user consent. The activation actor is the building manager (or EMS operator), who oversees operation and ensures that self-consumption and flexibility commitments are respected. The setpoint definition combines a site import/export power in W with energy, SoC budgets (kWh, minimum reserves) and a self-consumption target, so surplus PV triggers BESS/EV charging while deficits or peak periods trigger controlled discharging, all within contracted capacity and device constraints. The activation mechanism relies on local measurements from the smart meter, PV inverter, BESS, and EVSE telemetry; the EMS computes and updates charge/discharge schedules in real time and issues commands via standard protocols (e.g., Modbus/IEC 61850 for BESS/PV; OCPP 1.6/2.0.1 or ISO 15118 for EVSE). This enables dynamic adjustment of charging rates and other controllable loads to maximize PV use, shave peaks, and minimize bills, while respecting user departure times, maintaining comfort, and providing graceful fallbacks (e.g., PV-surplus tracking with SoC floors) if communications are lost.

3.4 Innovative grid services suggested in the AHEAD project context

3.4.1 Western Europe Demo

Within the Western Europe Demonstrator (WED), which explores large-scale EVSE deployment across public, semi-public, and private infrastructures, as well as the electrification of maritime-tourism activities, the implementation of advanced flexibility services is essential to ensure both operational reliability and sustainable energy integration. Three services are particularly well aligned with the demonstrator's objectives: *Local Load management, Demand Response Participation, and Renewables Curtailment Mitigation.*

Local Load Management and Demand Response Participation are especially suited to the private infrastructures to be tested and validated, such as workplace and residential charging facilities. Local Load Management enables building-level energy management systems to dynamically adjust charging demand according to contracted capacity and site-level constraints, ensuring operational efficiency while avoiding local overloads. Similarly, Demand Response Participation based on price signals allows behind-the-meter assets, including EVs by offering cost optimisation for consumers and supporting grid balancing. These services are directly aligned with the WED's aim of assessing AI-driven coordination strategies in realistic private charging environments, where user behaviour, load diversity, and contractual limits strongly influence system performance.

Renewables Curtailment Mitigation supports European decarbonisation by using EV charging to absorb surplus renewable generation. In Madeira, where grid flexibility is limited, this service helps prevent renewable curtailment and stabilizes the island's power system. By aligning charging schedules with renewable availability through TSO signals, it increases the use of clean energy and reduces reliance on fossil-based generation, demonstrating the innovative scope of the Western Europe Demonstrator.

3.4.2 Nordic Europe Demo

Within the Nordic Europe Demonstrator (NED), which focuses on slow and fast chargers for light-duty electric vehicles across residential, workplace, and public settings, deploying targeted flexibility services is essential to ensure operational reliability and efficient grid integration. Three services are particularly well aligned with the demonstrator's objectives*:* *Frequency Regulation Services*, *Direct Load Management*, and *Peak Shaving*.

Frequency Regulation Services are especially suited to the Nordic Europe Demonstrator, which targets slow and fast charging for light-duty EVs across residential, workplace, and public sites. In this context, EVSE fleets modulate charging (V1G) and, where available, bidirectional power (V2G) in response to frequency deviations and operator setpoints, providing fast up/down regulation without breaching user mobility needs through SoC and departure time constraints. The service will validate AI-driven coordination to forecast availability, aggregate heterogeneous EVSE, and schedule sub minute setpoint changes under real driving patterns, cold-climate battery behaviour, and local tariff structures. By demonstrating reliable, standards-based response from both AC and DC infrastructure, the NED assesses how EV flexibility can contribute to system frequency stabilization while maintaining user comfort and operational practicality in Nordic conditions.

Direct Load Management with DSO inputs is especially suited to the Nordic demonstrator's residential, workplace, and public charging sites. It enables site level EMS and CPO platforms to adjust per connector setpoints in real time according to technical limits such as local transform capacity, voltage margins, and contracted capacity, ensuring operational efficiency while avoiding local overloads.

Peak Shaving is especially suited to the Nordic demonstrator's residential, workplace, and public charging sites. It enables site EMS and CPO platforms to limit coincident demand and contracted power by smoothing EV charging and co-dispatching on-site BESS, thereby reducing demand charges and avoiding local overloads. This service is directly aligned with the NED's aim of evaluating AI-driven coordination under centralized vs. distributed control in realistic Nordic conditions, demonstrating how predictive scheduling and real-time control keep demand within limits without compromising user experience.

3.4.3 Southern Europe Demo

Within the Southern Europe Demonstrator (SED), which assesses the feasibility of charging for private EVs and public-transport fleets (HDVs) and the amount of flexibility they can provide to the grid across multi-vendor deploying targeted flexibility services is essential to ensure reliable operation and scalable integration. Two services are particularly well aligned with the demonstrator's objectives: Congestion Management with DSO inputs, to respect local network constraints and contracted capacity while coordinating AC/DC sites and depot hubs; and Demand Response Participation, enabling BTM assets (EVSE, BESS, and V2X-capable fleets) to respond to market and operator signals, reducing costs for operators while supporting grid balancing.

In the Milan demonstration site, an EVSE will be installed and used as a testbed for flexibility functionalities with the distribution grid. The innovation lies in the dynamic interaction between the charging infrastructure and the DSO, enabling real-time responsiveness to grid needs.

The Congestion Management service is activated when DSO measurements or forecasts indicate local network loading approaching contractual or technical limits, prompting coordinated control of AC/DC chargers and depot hubs to redistribute or limit power flows. The Demand Response Participation service is triggered by market or operator signals requesting flexibility, allowing BTM assets such as EVSEs, battery energy storage systems, and V2X-capable fleets to modulate their power profiles and deliver upward or downward flexibility according to market or grid conditions.

During the demo, the DSO will be able to send real-time flexibility requests to the charging station. These requests may include commands to reduce energy consumption during periods of grid stress or inject energy back into the grid when there is surplus capacity available in the connected battery system.

This setup will allow the EVSE to act not only as a consumer but also as a prosumer in the form of a distributed energy resource (DER), contributing to grid stability. The Milan demo will thus showcase how smart charging and bidirectional energy flows can be used to support the energy transition and enable more intelligent, responsive distribution networks.

4 ADVANCED CONVERTER TOPOLOGIES AND TECHNOLOGIES FOR EVS, HDVS, VESSELS

The rapid growth of electric mobility is not only reshaping energy demand patterns but also accelerating innovation in power electronics, which forms the backbone of charging infrastructure and vehicle-grid interactions. Converter technologies are central to this evolution, as they determine how efficiently and flexibly EVs, HDEVs, and electrified vessels interface with the grid. Advances in semiconductor devices and high-frequency components, improved efficiency, reduced size and cost, and enhanced grid support functionalities. These developments are particularly relevant as the diversity of applications expands, ranging from residential EV charging to megawatt-scale systems for trucks, buses, and maritime transport.

This section examines advanced converter topologies and technologies that underpin the integration of electric mobility into power systems. It begins with an overview of charging system architectures, before distinguishing between on-board and off-board EVSEs designs and their respective implications for grid interaction. The analysis then extends to high-power converter solutions tailored for HDEVs, addressing their unique charging requirements, and finally considers converter topologies for electrified vessels and maritime applications, where operational scales and technical conditions differ significantly from road transport.

4.1 Advanced converter topologies for grid support

To support the rapid passes of electric mobility, advanced charging systems are required, especially those capable of bidirectional power flow, allowing not only battery charging but also energy feedback to the grid. These smart and bidirectional charging architectures are essential to optimize energy use, support grid stability, and enable V2G services.

Central to these architectures are power electronic converters, which manage the flow of electricity between the grid and vehicle batteries. To be suitable for these purposes, converters must meet several important requirements. They must provide bidirectional capability to enable both grid-to-vehicle (G2V) and V2G power flow. High efficiency, typically above 95%, is necessary to reduce energy losses and improve overall system performance. Converters also need to comply with grid standards and support both AC and DC interfaces to ensure seamless integration. Furthermore, modularity and scalability are key to adapt converter designs from small EV chargers to large vessels. Electrical isolation is mandatory in many applications for safety and noise reduction. Finally, modern converters must be ready for smart control and communication, enabling advanced energy management and seamless interaction with smart grids, and they should include local measurement of voltage and frequency to ensure proper and timely response to grid events. This section provides a comprehensive review of the most relevant converter topologies for smart and bidirectional charging systems. The focus is on converter designs suitable for simulation, highlighting their operating principles, advantages, limitations, and applications in EVs, HDVs, and marine vessels.

4.2 Charging System Overview

Battery charging systems for EVs can generally be classified into on-board and off-board architectures. Figure 1 illustrates a general EV charging system architecture, showing the interaction between on-board and off-board components, and highlighting key elements relevant to smart and bidirectional energy management.

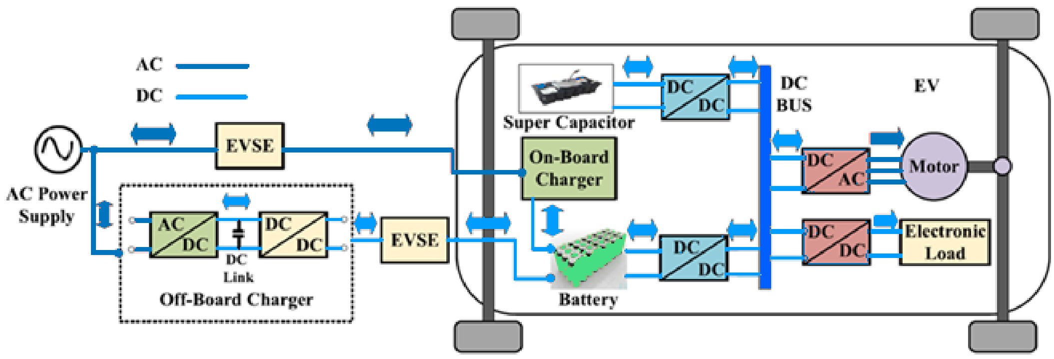


Figure 1 – Charging system schematic including both on-board and off-board chargers [37].

4.2.1 On-board chargers

On-board chargers (OBCs) are compact power electronic units integrated into EVs that enable direct connection to the AC power grid. Their primary function is to convert alternating current (AC) into regulated Direct Current (DC) for battery charging, while meeting grid requirements such as high-power factor, Low Total Harmonic Distortion (THD), and electrical isolation for safety. OBCs are constrained by limited installation space, weight, thermal management, and electromagnetic emission control, which shape their design and performance. Typical power ratings range from 3.3 kW to 43 kW, covering single-phase AC charging (mode 1: 0–3.7 kW, mode 2: 3.7–7 kW, and mode 3: 7–22 kW) as well as three-phase AC charging up to 43 kW, offering slower to medium charging speeds suitable for residential and commercial use [37]. While most OBCs traditionally support unidirectional power flow, from the grid to the EV, recent developments have introduced bidirectional solutions, enabling advanced services such as V2G, vehicle-to-home (V2H), and vehicle-to-load (V2L). Depending on their configuration, OBCs based on the configurations of stages can be classified mainly as: Two stage, Single stage as shown in Figure 2. However, the integrated and multifunctional chargers are also included in this category [38].

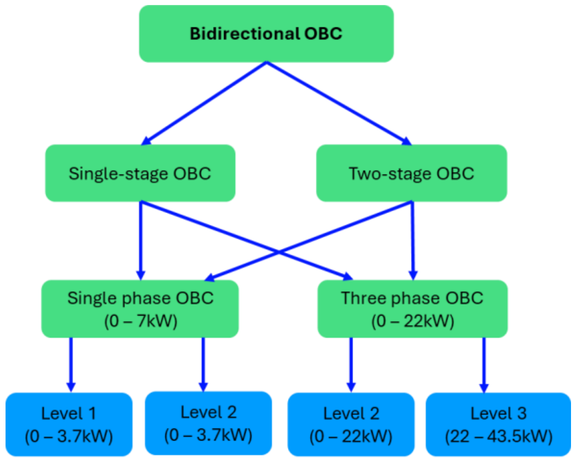


Figure 2 – Classification of OBC systems [38].

The most advanced category of on-board chargers is the multifunctional OBC, which integrates multiple functionalities by sharing components across different systems. This approach leads to more compact and lightweight designs, while also enhancing overall efficiency. For example, a recent design [39] (shown in Figure 3) employs a dual-function strategy with comparable capabilities, effectively combining diverse charging and power management tasks within a single unit.

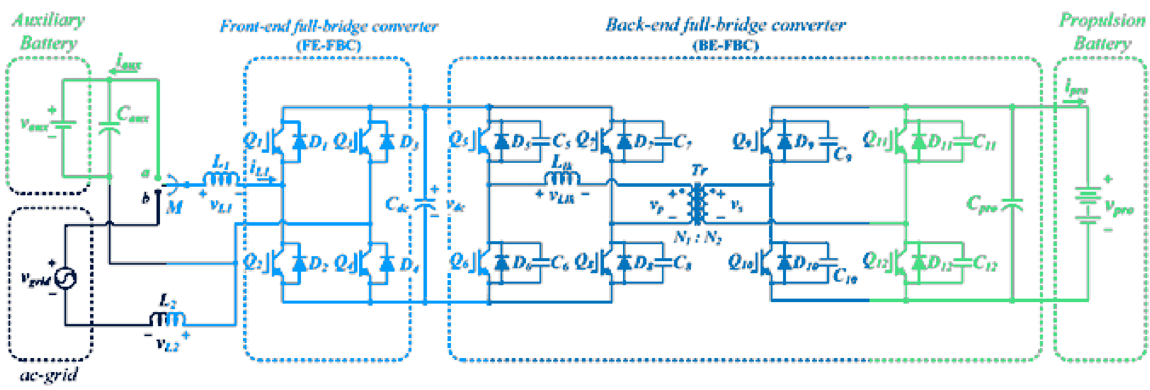


Figure 3 – Charging system schematic employing a dual-function strategy.

For smart and bidirectional charging architectures serving high-power applications like HDVs and vessels, off-board chargers are essential due to critical limitations of OBCs. OBCs impose strict weight, volume, and cost constraints on EVs, making them impractical for megawatt-scale charging demands. Off-board solutions decouple power electronics from the EV, enabling scalability to extreme power levels (100 kW–3 MW+), advanced grid integration (active power regulation, black-start capability), and centralized optimization of bidirectional energy flows (V2G, V2B). This architecture reduces EV complexity, eliminates redundant power conversion stages, and allows utilities to deploy unified control systems for fleet charging, grid balancing, and renewable energy buffering. For maritime and heavy transport, where space efficiency and rapid charging are paramount, off-board chargers represent the only viable path toward electrification.

Consequently, this report primarily concentrates on off-board charging systems to address the high-power, bidirectional, and smart-grid requirements of modern EV/HDV/vessel charging infrastructure.

4.2.2 Off-board chargers

Level 3 chargers or mode 4 chargers, due to their high-power ratings, are typically designed as off-board systems (installed externally to the EV). A wide variety of off-board charger configurations have been explored in the literature [40]. In compliance with the IEC EN 61851-23 standard, galvanic isolation between the AC input and DC output circuits is mandatory. Therefore, this section focuses exclusively on isolated off-board charger topologies.

A standard off-board charging system consists of two primary stages: *i)* a grid-side AC/DC converter for both unidirectional and bidirectional capabilities and *ii)* a DC/DC converter that interfaces with the EV battery, as well as for both unidirectional and bidirectional capabilities. Depending on the converter topology, both stages can support either unidirectional or bidirectional power flow. However, the main purpose of this task is research about smart and bidirectional charging architectures and only these categories are discussed. Meanwhile, these can be isolated (with galvanic isolation) or non-isolated, depending on safety requirements. But due to the EMI and safety requirements for smart charging, isolated topologies are the main scope of this task. The topologies are further differentiated by their modulation techniques, control schemes, and power densities.

4.3 Bidirectional AC/DC Converter Topologies for EV Charging

AC/DC converters interface the charger with the utility grid and play a critical role in power quality, grid compliance, and overall charging system efficiency. In a bidirectional configuration, these converters not only ensure seamless energy transfer from the grid to the EV battery but also support reverse power flow back to the grid during V2G operations.

Key design goals include high efficiency, power factor correction (PFC), low total harmonic distortion (THD), and compliance with grid codes (such as IEEE 1547 and EN 50549). The topologies can be classified also based on three-phase or single-phase point of view. Below are the most common AC/DC bidirectional converter topologies used in smart EV charging systems, especially for medium- and high-power applications:

4.3.1 2-Level Full Bridge with PFC

The two-level full-bridge converter is the most basic and widely used topology for bidirectional EV charging [41], [42]. It consists of four switches in a full-bridge configuration and typically includes a boost or buck-boost PFC stage. During charging, it rectifies the AC grid voltage and regulates the DC output voltage; during discharging (V2G), it inverts the DC battery voltage back to AC, injecting current into the grid with high power factor. While it offers simplicity and cost-effectiveness, it suffers from high switching losses and electromagnetic interference (EMI) at higher power levels due to its two-level operation.

4.3.2 T-Type Three-Level converter

The T-type inverter is a three-level converter that offers reduced voltage stress on the switches and lower switching losses compared to the traditional two-level topology. It introduces an additional bidirectional switch per phase, enabling three voltage levels at the output (+Vdc/2, 0, -Vdc/2). This improves efficiency and reduces THD in the current output. The T-type structure is particularly attractive for medium-voltage EVSEs due to its better efficiency and power quality performance, though it is more complex to control and requires precise balancing of the DC-link capacitors [43], [44].

4.3.3 Neutral-Point Clamped (NPC) Converter

The Neutral-Point Clamped (NPC) converter, also known as a diode-clamped three-level converter [45], [46], divides the DC bus into three voltage levels using clamping diodes and capacitors. It provides better waveform quality and lower voltage stress on the switches, making it suitable for high-power EVSEs. Its main drawback is the uneven voltage stress across the clamping diodes and challenges in neutral-point voltage balancing. However, with proper modulation and control, NPC converters can achieve high efficiency and low harmonic distortion in grid-connected operations.

4.3.4 Vienna Rectifier

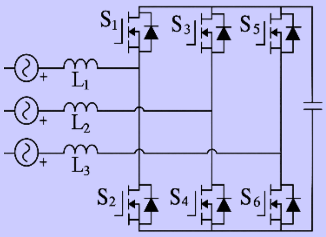
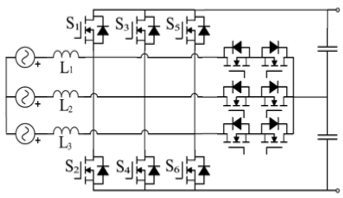
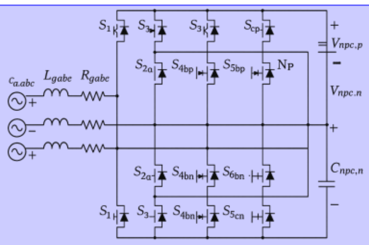
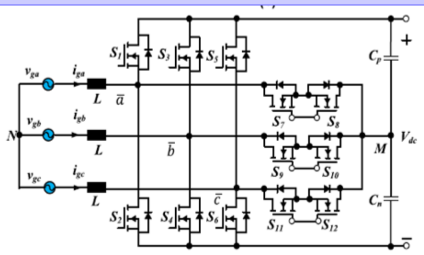
The Vienna rectifier is a unidirectional three-phase three-level converter with inherently low THD and high efficiency. It uses three bidirectional switches and diode paths to realize three-level operation on the DC side, with power factor correction on the AC side. While traditionally designed for unidirectional operation (i.e., only grid-to-vehicle), modified versions with bidirectional capability are being explored for smart charging applications [47], [48]. The

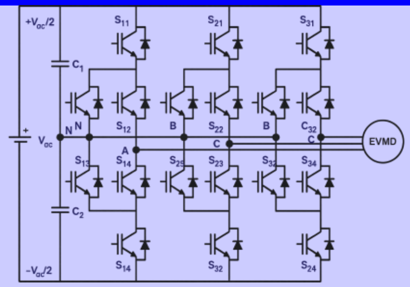
Vienna rectifier is compact and efficient but lacks native support for V2G unless extended with additional inverter stages.

4.3.5 Active NPC (ANPC)

The Active NPC (ANPC) converter improves upon the classical NPC by replacing passive clamping diodes with active switches, enabling better control over voltage sharing and thermal stress among devices. This enhances reliability and efficiency, especially at higher power ratings. The ANPC can be used in both charging and discharging modes, offering excellent performance in terms of output waveform quality, switching loss reduction, and fault tolerance. It is particularly suited for fast-charging stations requiring high power density and robustness under grid disturbances [49], [50].

Table 3 – Comparison table of bidirectional converter topologies for AC/DC stage.

Converter Topology	Normal power range	Efficiency	Complexity	Use Case	Ref
 **2-Level Full Bridge**	3–100 kW+	94–96%	Low–Medium	Off board	[41], [42]
 **T-Type Inverter**	>10 kW	96–98%	Medium	Off board	[43], [44]
 **Neutral-Point Clamped (NPC)**	>10 kW	95–97%	High	Off board	[45], [46]
 **Vienna Rectifier**	3–22 kW	96–98%	Medium	Usually, On-board	[47], [48]

Converter Topology	Normal power range	Efficiency	Complexity	Use Case	Ref
 Active NPC (ANPC)	>20 kW	>97%	High	Off board	[49], [50]

4.4 Bidirectional DC/DC Converter Topologies for EV Charging

Bidirectional DC/DC converters play a crucial role in smart EV charging systems by interfacing the battery with the DC-link (in off-board chargers) or directly with the DC fast-charging infrastructure. These converters are essential in enabling V2X functionalities, allowing energy to flow both from the grid to the vehicle and vice versa. The key design objectives are high efficiency, high power density, galvanic isolation (where needed), and precise bidirectional current control. Below are the most prominent bidirectional DC/DC topologies used in modern EV charging systems:

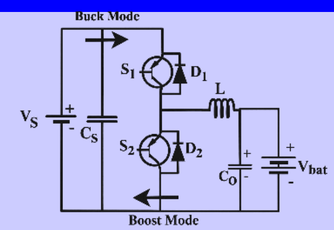
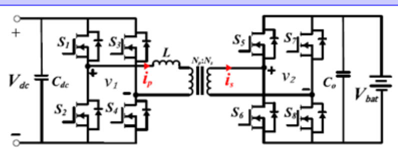
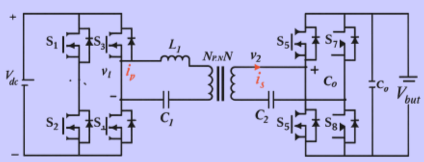
- **Bidirectional Non-Isolated Boost/Buck-Boost Converter:** This is the simplest bidirectional DC/DC topology, where a single inductor and two active switches allow step-up and step-down conversion. In boost mode, it charges the battery from the DC-link, and in buck mode, it discharges energy back to the grid or other loads. It is suitable for low to medium power onboard applications due to its compact design and relatively high efficiency. However, it lacks galvanic isolation, which limits its use in safety-critical off-board systems [51], [52].
- **Dual Active Bridge (DAB) Converter:** this converter is one of the most popular isolated bidirectional DC/DC topologies. It uses two full-bridge inverters connected via a high-frequency transformer. Power flow is controlled by adjusting the phase shift between the bridges. It supports both soft-switching and high-power density, making it ideal for medium-to-high power off-board fast chargers and V2G systems. Different types of DAB converters are discussed in [53], [54].
- **Capacitor Resonant Converter (CLLC) (Bidirectional):** The CLLC resonant converter is an isolated topology based on resonant tank networks. It provides zero-voltage switching (ZVS) and zero-current switching (ZCS) in both directions, significantly reducing switching losses. The bidirectional version uses two active

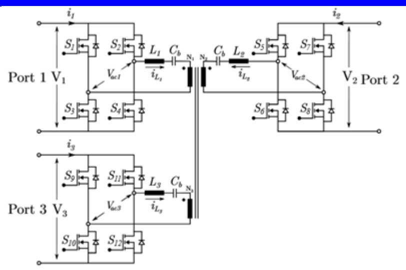
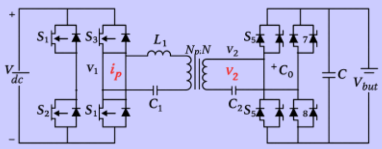
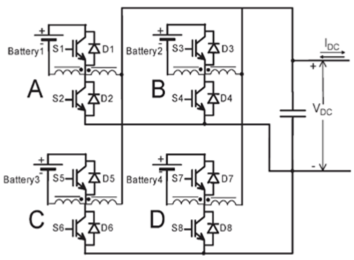
bridges and a symmetrical control strategy. It is increasingly used in high-frequency isolated chargers due to its efficiency and EMI performance [55], [56].

- **Triple Active Bridge (TAB) Converter:** The Triple Active Bridge extends the DAB concept by connecting three active bridges via a multi-winding transformer. This topology enables multi-port energy management, for example, simultaneously connecting a PV panel, battery, and grid. It is ideal for energy hubs where power flow between multiple sources and sinks must be dynamically balanced [57], [58].
- **LCL Resonant Converter:** LCL Resonant Converter is indeed a viable and increasingly researched topology for the DC/DC stage in smart EV charging systems, especially in wireless power transfer (WPT) or high-efficiency isolated charging scenarios. They offer soft switching (ZVS or ZCS) for reduced switching losses. They are Suitable for high-frequency operation, often used in inductive wireless charging [59], [60].

- **Bidirectional flyback converter:** The flyback converter offers isolation through a transformer but is typically used in low-power applications due to its higher voltage stress and limited efficiency. It can be designed in a bidirectional configuration for onboard auxiliary converters or very compact chargers [61].

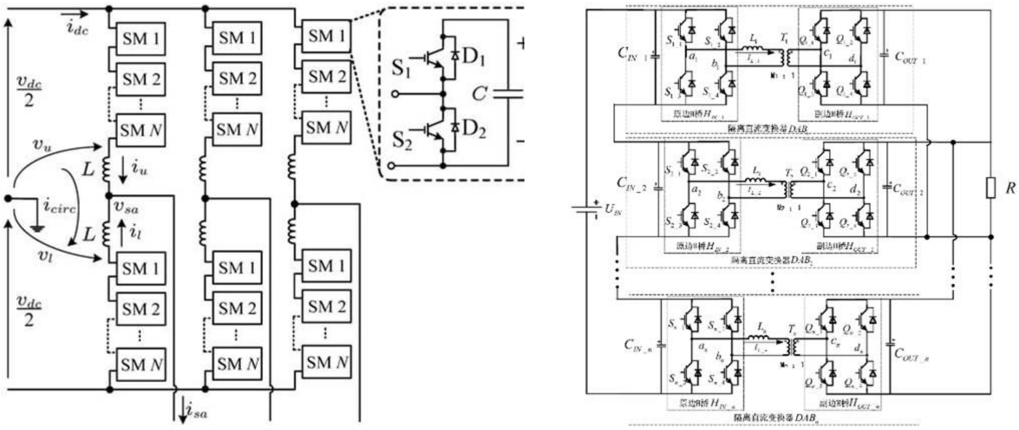
Table 4 – Comparison table of bidirectional converter topologies for DC/DC stage.

Converter Topology	Control Complexity	Efficiency	Power Range	Use Case	Ref
 **Buck/Boost (Non-Isolated)**	Low	Medium	Low–Medium	Onboard chargers	[51, 52]
 **Dual Active Bridge (DAB)**	Medium	High	Medium–High	Off-board chargers, V2G	[53, 54]
 **CLLC Resonant Converter**	High	Very High	Medium–High	Wireless charging, off-board fast charging	[55, 56]

Converter Topology	Control Complexity	Efficiency	Power Range	Use Case	Ref
 **Triple Active Bridge (TAB)**	High	High	Medium–High	Energy hubs with multi-port control	[57, 58]
 **LCL Resonant Converter**	High	97–99%	10–100 kW	Fast DC charging, off board	[59, 60]
 **Flyback (Bidirectional)**	Medium	Low	Low	Compact onboard/auxiliary charging	[61]

4.5 Converter Topologies for Heavy-Duty EV Charging

Heavy-duty EV charging infrastructure demands robust, high-power converter solutions capable of handling hundreds of kilowatts to multiple megawatts. The converter topologies used in these applications must support bidirectional power flow, ensure high efficiency, and often provide galvanic isolation for safety and compliance with grid codes. The AC/DC stage typically includes NPC, multi-level, or Active Frontend (AFE) converters, optimized for power factor correction and reduced harmonics at high power levels. On the DC/DC stage, isolated topologies such as the DAB, LLC resonant converters, and phase-shifted full-bridge (PSFB) converters dominate due to their ability to efficiently transfer large power while maintaining soft switching and bidirectional operation. These converters are integral in fast-charging stations and heavy-duty fleet applications, enabling efficient energy transfer between the grid and vehicle batteries [62], [63].



(a) (b)

Figure 4 – Configuration of multi-level converter suitable for HDEVs. a) MMC converter for AC/DC stage [26] b) Cascade DAB converter for DC/DC stage [63].

4.6 Converter Topologies for Electrified Vessels and Maritime Applications

Electrification of vessels and maritime applications introduces unique challenges, including harsh environmental conditions, strict safety standards, and the need for highly reliable and efficient power conversion systems. Converter topologies for these applications typically operate at power levels ranging from hundreds of kilowatts to several megawatts and prioritize galvanic isolation to protect sensitive onboard equipment. The AC/DC conversion stage commonly employs ANPC and MMC for their scalability, fault tolerance, and high efficiency in managing shore-to-ship or onboard power flow. On the DC/DC side, DAB and LLC resonant converters are preferred due to their soft switching capabilities, high efficiency, and suitability for bidirectional power transfer in battery management systems. These advanced converters enable seamless integration of energy storage, renewable energy sources, and grid connections within the maritime environment, supporting the transition towards greener and more sustainable shipping [64].

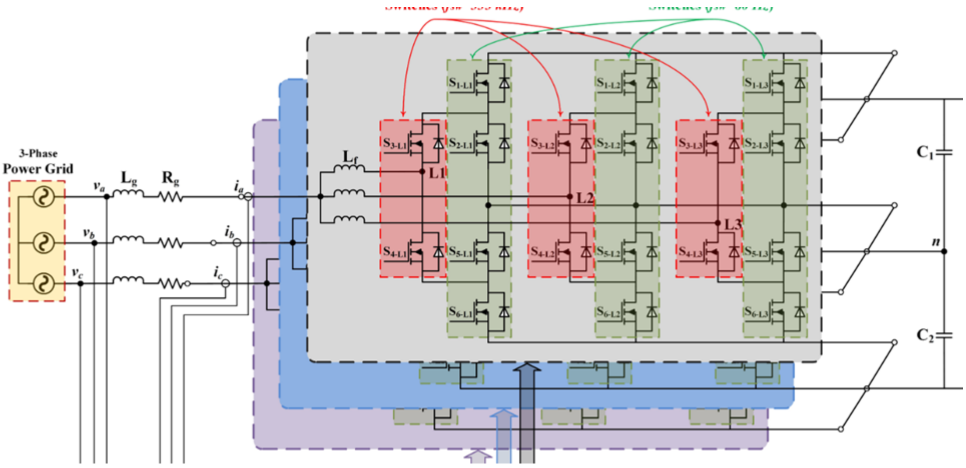


Figure 5 – Configuration of multi-level converter suitable for Maritime [64].

The table provides a comprehensive overview of recommended converter topologies segmented by application type, ranging from passenger EVs, HDVs such as trucks and buses, to maritime vessels and ports. For passenger EVs, wired solutions commonly use ANPC 3-Level converters at the AC/DC stage paired with DAB converters at the DC/DC stage, offering bidirectional power flow, moderate scalability, and high efficiency suitable for home and public chargers. Wireless charging introduces more complexity, often requiring resonant converters like CLLC, which add magnetic isolation and dynamic tuning for effective power transfer. Heavy-duty vehicles prioritize robust and scalable topologies such as interleaved DAB and ANPC or T-Type 3-Level converters, balancing high power capacity with efficiency and thermal management. In maritime applications, converters such as MMC and high-power CLLC/DAB hybrids are favoured due to their ultra-high scalability, fault tolerance, and suitability for large-scale charging infrastructure. Notably, many of these topologies integrate smart control features supporting V2G functionality, enabling bidirectional energy flow and advanced grid services. This diversity of topologies highlights the need to tailor converter design to specific application requirements, balancing efficiency, isolation, scalability, and control complexity to meet the evolving demands of smart EV charging ecosystems.

Table 5 – Suggested classified table of bidirectional converter topologies for all segments.

Segment	Charging Type	Stage	Recommended Topology	Bidirectional	Isolation	Scalability	Efficiency	Smart Control	Notes
EVs	Wired	AC/DC	ANPC 3-Level	✓	-	Moderate	High (~97%)	✓	Ideal for home/public chargers; good THD and reactive power control
	Wired	DC/DC	Dual Active Bridge (DAB)	✓	✓	Moderate	High (~95–97%)	✓	Compact, efficient, soft switching
	Wireless	AC/DC	ANPC 3-Level	✓	-	Moderate	High	✓	Shared with wired systems
	Wireless	DC/DC	CLLC Resonant	✓ (with control)	✓ (magnetic)	Moderate	High (~94–96%)	(more complex)	Compact coils; supports dynamic wireless; requires tuned control
Vessels/Port	Wired	AC/DC	MMC (Modular Multilevel Converter)	✓	-	Ultra-High	Medium–High	✓	Ideal for MW-scale, flexible cells, superior fault tolerance
	Wired	DC/DC	Modular Multilevel DC/DC (M2DC)	✓	✓	Ultra-High	Medium–High	✓	Used in port electrification, scalable, modular, expensive
	Wireless	AC/DC	MMC or Cascaded ANPC	✓	-	Ultra-High	Medium	✓	Ports may adopt contactless charging in future
	Wireless	DC/DC	High-Power CLLC / DAB	✓	✓	Ultra-High	Medium	— (experimental)	High-power IPT still in pilot phase, suitable for stationary dock systems
HDVs (trucks, buses)	Wired	AC/DC	ANPC or T-Type 3-Level	✓	-	High	High	✓	Handles higher voltages and currents
	Wired	DC/DC	Interleaved DAB	✓	✓	High	High	✓	Parallel units improve scalability and thermal performance
	Wireless	AC/DC	ANPC or T-Type 3-Level	✓	—	High	High	✓	Same grid-side architecture
	Wireless	DC/DC	Interleaved CLLC	✓	✓ (magnetic)	High	Medium–High	—	More complex control for wide power range

4.7 Assessment of semiconductor technologies and high-frequency components

The performance and scalability of advanced power converters in electric mobility are directly linked to progress in semiconductor technologies and medium/high-frequency passive components. These determine conversion efficiency, volumetric power density, reliability, and overall cost. In this section, we evaluate modern and prominent semiconductor devices and medium/high-frequency component technologies with application-specific emphasis for EVs, HDVs and electrified vessels.

4.7.1 Modern and prominent semiconductor technologies for grid connected and mobility applications

Power semiconductors act primarily as high-frequency switches, and their performance is strongly determined by material properties such as bandgap, critical electrical field, and thermal conductivity. Silicon (Si) devices remain cost-effective and dominant in low- and medium-power applications while modern wide-bandgap (WBG) devices, in particular Silicon Carbide (SiC) and Gallium Nitride (GaN), are enabling significant improvements in overall system performance [62].

For the challenges of EV fast-charging systems SiC Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) are increasingly replacing Si Insulated-Gate Bipolar Transistor (IGBTs) [63]. For the same operating voltages SiC MOSFETs enable higher switching frequencies reducing passive filters and isolation transformer volume, a critical factor for compact EV powertrains, OBC, and high efficiency EVSEs. Demonstrations have already shown >98% converter efficiency in 800 V charging systems, translating to faster charging with reduced thermal management overhead [64].

HDEVs charging as well as high-power traction in buses or trucks demand devices capable of handling several hundred kilowatts. SiC devices with blocking voltages up to 10–15 kV [65] are being tested in modular multilevel converter (MMC) stages for megawatt-scale charging hubs [65]. Their higher thermal conductivity simplifies cooling in confined depots.

In vessels and aircraft, power density is of even greater importance. GaN high-electron-mobility transistors (HEMTs), although currently limited to 650 V ratings, enable high-frequency operation in the MHz range, enabling ultra-compact converters [66].

Other semiconductor technologies have yet to achieve technological maturity for industrial use, ultra-wide bandgap semiconductors such as Ga_2O_3 and diamond offer promising pathways for extremely high-voltage and high-temperature devices, though they remain limited to research applications [67].

4.7.2 High-Frequency Passive Components for Compact and Efficient Design

Raising converter switching frequency is a direct pathway to reducing the size of transformers and filter inductors and capacitors Medium-frequency transformers (10–50 kHz) are already being integrated into isolated DC/DC converters for EVs and HDVs, reducing footprint while still handling several hundred kilowatts [68].

In terms of materials, ferrites have been extensively used in medium frequency applications up to a few dozen kW. More recently amorphous and nanocrystalline materials have been considered due to their inherent magnetic properties [69].

For EVSEs: medium and high-frequency transformers reduce isolation stage volume, enabling modular and scalable charging units and among different constructive methods planar transformers are being utilized due to a fine control of the leakage inductance that is crucial for some power converters operation (e.g. Dual Active Bridge) [51].

Electrolytic capacitors are one of the limiting factors in terms of converter lifetime and operation temperature limits and a common trend is to actively monitor these assets [50]. The use of higher operating frequencies as well converter topologies that actively switch these devices enable the use of different capacitors technologies namely solid dielectric capacitors such as plastic film or ceramic capacitors.

4.7.3 Implications for Grid Services

The choice of semiconductor and HF component technologies has direct consequences on the type and quality of grid services that EVs, HDEVs, and vessels can provide:

- SiC/GaN devices with lower switching losses enable converters to switch at higher frequencies increasing control bandwidth and enable participation in fast frequency and voltage support services, critical in weak grids and microgrids.
- Efficiency gains from reduced losses in semiconductors and passive components translate into reduced thermal footprint, without oversizing cooling systems and smaller thermal cycling. Both aspects are critical for economic viability of these solutions by increasing reliability and reducing the investment costs.

5 COMMUNICATION PROTOCOLS AND BATTERY PASSPORTS FOR GRID INTEGRATION

The effective integration of electric mobility into power systems depends not only on advanced charging technologies but also on secure and interoperable communication frameworks. Standardised communication protocols between EVSEs and central management systems are essential for enabling coordinated control, flexibility services, and reliable interaction with grid operators. In parallel, the emerging concept of the battery passport provides a digital record of battery characteristics and lifecycle data, supporting traceability, sustainability, and grid-aware operation.

This subsection reviews the communication protocols that enable the integration of EVs into the power system, as well as the provision of grid services, alongside battery passport initiatives, with the aim of identifying advanced strategies to enhance grid support and scale e-mobility adoption.

5.1 Communication protocols for grid support

EV grid integration relies on communication protocols to enable efficient charging, energy management, and grid stability. These protocols provide a set of rules and guidelines to ensure compatibility and facilitate communication and data exchange between EVs, EVSEs, central point management system (CPMS), grid operators, and other stakeholders [65]. Additionally, EV charging protocols enforce safety standards, addressing physical and cyber security concerns to protect vehicles, passengers, and data from potential hazards.

Communication protocols can be divided into front-end and back-end protocols [65]. Front-end protocols focus on the interaction between the EV and the EVSE. Back-end protocols, emphasises communication between the EVSE and the Charging Management System (CMS) services, including user authentication, billing, and remote monitoring [5]. Protocols for grid support can be split into different sections depending on the communicating components.

Protocols for EV grid integration and their application are detailed below:

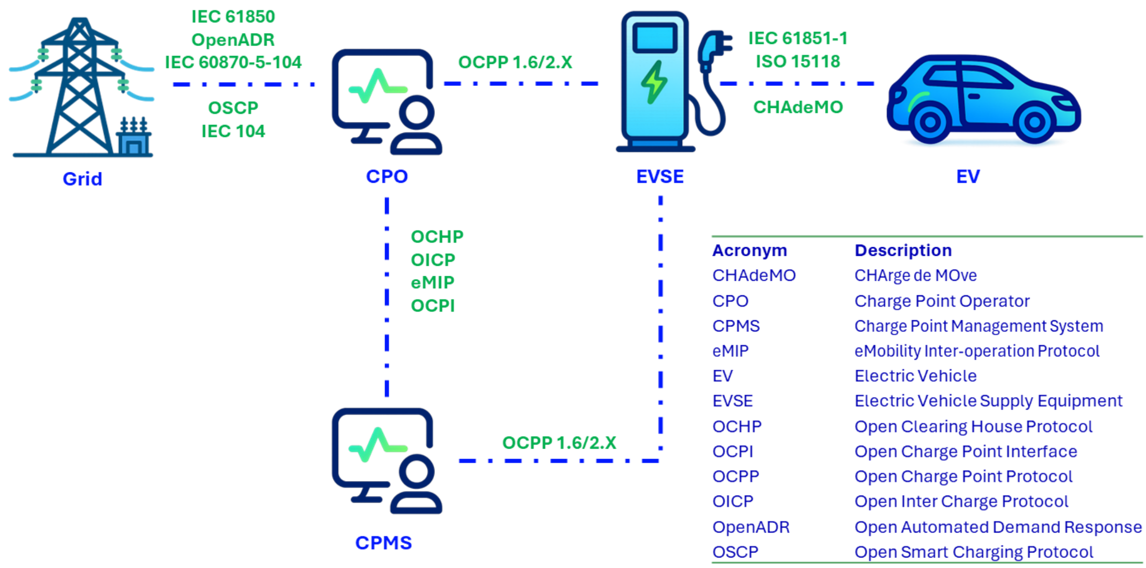
- **Open Charge Point Protocol (OCPP):** Charging station – Backend communication
- **Open InterCharge Protocol (OICP), Open Clearing House Protocol (OCHP), Open Charge Point Interface (OCPI), eMobility Interoperation Protocol (eMIP):** Roaming platform operator – Backend
- **Open Automated Demand Response (Open ADR):** Flexibility aggregator – Assets
- **ISO 15118:** Vehicle – Charging station

- **IEC 61851-1:** Vehicle – Charging station
- **CHAdeMO:** Vehicle – Charging station
- **Open Smart Charging Protocol (OSCP), IEC 61850, IEC 60870-5-104, IEC 104:** DSO or others - Backend
- Proprietary communication protocols

These different protocols and standards are important to facilitate:

- Interoperability
- Scalability
- Security
- Efficiency and Smart Charging
- User Experience
- Regulatory Compliance

Together, these factors ensure that EV charging systems are streamlined, reliable, accessible, and secure, and that they are ready to meet future demands by enabling an infrastructure of compatible entities, seamless data exchange, freedom of choice, cost savings, better services, increased competition, ongoing innovation, and scalability [65]. Figure 6 shown a description of the protocols and standards found most relevant.



Acronym	Description
CHAdeMO	CHArge de MOve
CPO	Charge Point Operator
CPMS	Charge Point Management System
eMIP	eMobility Inter-operation Protocol
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
OCHP	Open Clearing House Protocol
OCPI	Open Charge Point Interface
OCPP	Open Charge Point Protocol
OICP	Open Inter Charge Protocol
OpenADR	Open Automated Demand Response
OSCP	Open Smart Charging Protocol

Figure 6 – Main standards overview.

OCPP: Charging station – Backend: OCPP is a widely used EV charging communication protocol between an EVSE and the CMPS, available from and maintained by the Open Charge Alliance (OCA). Three versions are currently available: OCPP 1.6 (2015) introduced basic smart charging features for load balancing and simple device management; OCPP 2.0.1 (2020) added advanced smart charging and full device management, strengthened security, and support for ISO 15118; and OCPP 2.1 (2025), the newest version of the Open Charge Point Protocol, expands support to bidirectional charging (V2G), improves integration with renewable energy sources, offers flexible payment and transaction options (energy-, time-, and cost-based), adds support for battery swapping stations and local cost calculation at chargers, and maintains backward compatibility with OCPP 2.0.1

- **OCHP, OICP, eMIP, and OCPI:** These are all protocols developed by different entities, e.g., OICP developed by Hubject in 2012, that serve almost identical purposes and allow communication between or CPMS and a clearinghouse, to enable *roaming,* which allows drivers to charge on EVSE's outside those provided by their e-mobility service provider [66].

- **Open ADR: Flexibility aggregator – Assets:** Open ADR is maintained by The Open ADR Alliance and facilitates automated and secure two-way communication between electricity providers, system operators, and end-users. It enables demand response service providers to communicate signals directly to customers using a common language and existing communications, such as the Internet. Further, it allows manufacturer-independent and secure communication [65].

- **ISO 15118: Vehicle – Charging station:** This front-end protocol, published in 2013 by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC), is an international standard that defines the communication between EV and EVSE. The protocol enables plug & charge, smart charging, bidirectional charging (V2G), security and authentication. It enhances the charging process by facilitating seamless communication between EVs and charging stations.

- **IEC 61851-1: Vehicle – Charging station:** IEC-61851-1 is a front-end standard for the definition of EV charging modes: Mode 1 with EV connected directly to AC grid (not allowed in EU), Mode 2 EV connected to AC grid through cable with control pilot and protection against electric shock, Mode 3 EVSE connected to AC grid with tethered cable, Mode 4 EVSE rectifies AC grid and supplies DC power to EV with tethered cable [67].

- **CHAdeMO, Vehicle – Charging station:** CHAdeMO is a front-end communication protocol maintained and developed by the CHAdeMO organisation. The protocol is used for DC charging and the v2.0 specification includes the possibility for bidirectional power transfer and the exchange of battery's state of charge (CHAdeMO 2019a). The CHAdeMO protocol adheres to IEC 61851.

- **OSCP - DSO or others – Backend:** The OSCP is a protocol used to exchange predictions of available power between a CPO and a DSO or similar party. OSCP is supported by the OCA [68].
- **Proprietary communication protocols:** Proprietary communication protocols are also often used, and the reasons may differ: They include customization for specific functionalities, control over technology and intellectual property, performance optimization, and enhanced security features. However, the use of proprietary protocols can create interoperability challenges, making it difficult for different systems and devices to communicate effectively.

5.2 Battery passport: definition and role

The EU's digital battery passport is a new initiative under EU regulations for ecodesign and batteries as part of the 'European Green Deal'. It helps companies track and share important data about batteries, such as their environmental impact, material sources, lifespan, repairability, and recyclability. The system will be mandatory from February 1, 2027, for all EVs and industrial batteries over 2 kWh sold in the EU, and the responsibility lies with economic operator who puts the battery on the market [69]. Each battery will have a QR code that provides access to this data. Specifications on what this data should include is also provided to ensure that batteries are operational and efficient to comply with minimum requirements. In short, this includes unique identification, type and model of battery, updates on performance and durability during repair and repurposing of the battery, and carbon footprint of manufacturing [70]. As proof of concept a prototype of the passport has been developed by GBA which shall act as a framework for companies [71]. One such example can be found from LG Energy Solutions (LGES), as illustrated by Figure 7 [72], which illustrates how the information and labelling can be accessed once the QR code has been scanned [73].

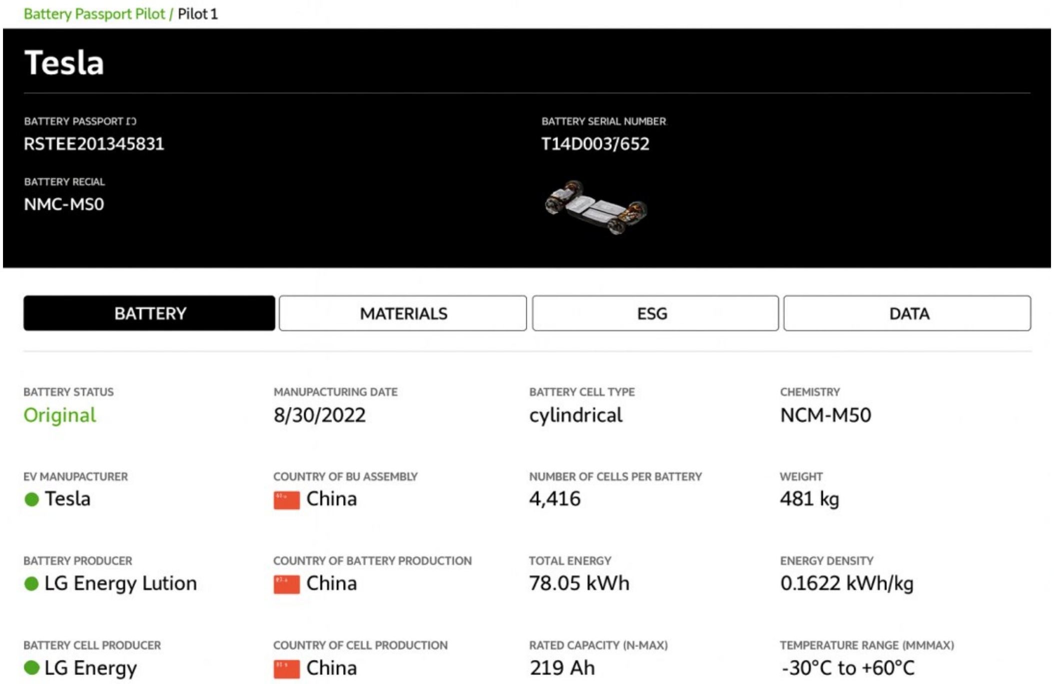


Figure 7 – Example of a Battery Passport from LG Energy Solutions (LGES).

To follow up with the EU battery legislation, the Chinese government launched the development of a Chinese digital battery passport, where similar information regarding the batteries is required [74].

5.2.1 Benefits and Criticism of Battery Passport

The battery passport improves transparency by tracking raw materials, their origins, and how batteries move through the supply chain. It helps with better recycling, supports the circular economy, and makes it easier to monitor sustainability efforts. It also creates fair competition for all businesses in the industry [75]. Nevertheless, there are concerns about data privacy and who controls the information. Some fear that managing and securing battery data could be costly and complex, especially for small and medium-sized businesses (SMEs) [81]. The lack of clear data-sharing standards could also make it difficult to connect different systems. In addition, manufacturers worry that the passport could create extra administrative work and increase production costs [80]. Further, there is recognized a diversity in this type of regulation which can impose challenges in terms of not having harmonization of the standards on an international level [82].

5.2.2 Planned and Implemented Standards

The EU Battery Regulation (Regulation (EU) 2023/1542) replaces the Battery Directive (2006/66/EC) and sets comprehensive rules for the sustainability, safety, and labelling of batteries placed on the market in the European Union. The main objective of the regulation is the introduction of the Battery Passport, ensuring transparency and traceability throughout the battery's lifecycle [83]. Additionally, the regulation mandates that all batteries must undergo a CE conformity assessment and eventually be CE marked, which is a responsibility that lies with the battery manufacturer [84]. To support the implementation of the Battery Passport, several relevant standards are applied and are described in the following:

- **DIN DKE SPEC 99100:** The mandatory data attributes for the Battery passport are defined by the *DIN DKE SPEC 99100 Standard,* which was launched in January 2025. These attributes include both general information on the battery, the material composition, carbon footprint data, performance of the battery, production process and disposal methods, as well as working conditions throughout the entire value chain [85].
- **ISO 14083:** Carbon footprint tracking is defined by ISO 14083, specifically for transport services. This standard specifies methodologies for calculating GHG emissions during battery production, usage, and disposal. It includes specific formulas, data inputs, and reporting requirements for organizations and transport services. Additionally, ISO 14083 includes a verification process to ensure accurate implementation of carbon footprint tracking, although the certification scheme is still under development [86].
- **IEC 62933:** To ensure safe and efficient operations of batteries, technical requirements for energy storage systems are defined by the IEC 62933 series of standards. This series includes definitions of terms applicable to EES systems, as well as specific standards for measuring the performance and safety of batteries. Furthermore, it sets safety standards to prevent electrical shocks, fires, explosions, etc., for grid-integrated batteries. IEC 62933 also provides guidelines for planning and installing energy storage systems and assesses their environmental impact, including how to minimize environmental harm [86].

6 CONCLUSIONS

This Deliverable set out to define innovative grid services for charging infrastructure by following a systematic path: first analysing grid specifications to identify technical constraints; then proposing a portfolio of services, including enhancements to bidirectional electric vehicle supply equipment (EVSEs) suited to those constraints; reviewing converter topologies to ensure credible grid support; and assessing advances in semiconductor technologies and high-frequency components to inform technology strategy. In parallel, the work evaluated communication protocols between charging stations and central management systems, as well as the emerging battery-passport framework, to secure interoperability, data integrity, and sustainable lifecycle management.

Upon a more detailed examination of the key findings, it becomes clear that:

- At the grid-operation level, the first analysis underscored that electric vehicle (EV) penetration directly stresses distribution feeders, transformers, and voltage margins, while also testing frequency stability and N–1 security at the transmission level. Uncoordinated charging amplifies these vulnerabilities, leading to overloads, voltage deviations, and reduced operational headroom. Addressing these constraints requires moving beyond traditional reinforcement planning towards flexibility-based strategies.

- Coordination through smart charging and vehicle-to-everything (V2X) can evolve EVs from passive loads into active grid resources. A taxonomy of innovative grid services, ranging from congestion management, voltage support, and phase balancing in distribution networks, to frequency regulation, contingency support, and renewable curtailment mitigation at transmission level, as well as behind-the-meter services for demand optimization and fairness, illustrates how charging infrastructures can be systematically mobilized to strengthen system operation. The validation within European demonstrators further shows that these services are not theoretical, but practically deployable under real technical and contractual settings.

- The provision of innovative grid services is inseparable from the capabilities of power electronic converters, which form the backbone of modern EVSE and vehicle-grid interactions. Advances in semiconductor devices, high-frequency magnetics, and modular topologies (such as Active Neutral-Point Clamped (ANPC), T-type three-level (T-type), Neutral-Point Clamped (NPC), Dual Active Bridge (DAB), Capacitor–Inductor–Inductor–Capacitor (CLLC)) enable bidirectional, efficient, and scalable power conversion across contexts, from residential On-Board Chargers (OBCs) to megawatt-scale off-board chargers for heavy-duty vehicles and maritime applications. By tailoring converter designs to application constraints, EVSE can provide not only reliable charging but also fast, accurate, and grid-compliant flexibility services.

- The communication protocols that standardize interactions across system layers are crucial. Protocols such as ISO 15118 (Road vehicles – Vehicle to grid communication interface), IEC 61851 (Electric vehicle conductive charging system), CHAdeMO (Charge de Move), and OCPP (Open Charge Point Protocol) define EV–EVSE interoperability and secure bidirectional control, while OpenADR (Open Automated Demand Response), OSCP (Open Smart Charging Protocol), and roaming interfaces (OCPI (Open Charge Point Interface), OICP (Open InterCharge Protocol), OCHP (Open Clearing House Protocol)) facilitate market participation, aggregation, and DSO/TSO coordination (Distribution System Operator / Transmission System Operator). These frameworks ensure that flexibility signals can be dispatched, enforced, and verified across heterogeneous infrastructures, providing the interoperability and cyber-security foundations on which innovative grid services depend.

- The battery passport introduces a data-centric innovation that extends grid services into the lifecycle dimension. By mandating transparency on battery composition, health, performance, and carbon footprint, the passport not only strengthens sustainability and circular-economy objectives but also enhances grid-aware operation. Verified state-of-health, safe operational windows, and traceable performance data allow system operators and aggregators to enrol assets more confidently in flexibility programs, align discharging cycles with warranty constraints, and improve settlement accuracy. While concerns on data privacy, standard harmonization, and (Small and Medium-sized Enterprises) costs remain, the passport represents a critical enabler of sustainable and scalable EV integration.

Taken together, these four dimensions, grid constraints, innovative services, enabling converters, and communication/data infrastructures, form a coherent framework for the next phase of e-mobility deployment. By combining advanced hardware intelligence with interoperable protocols, verifiable data governance, and market or/and regulatory adaptation, EV fleets can transition from sources of uncertainty to pillars of system resilience. The conclusion is clear: addressing the challenges of electrification requires not isolated solutions, but the orchestration of technologies, standards, and policies into a unified ecosystem where

EVs act as flexible, secure, and sustainable grid resources, thereby accelerating the clean energy transition.

REFERENCES

[1] IEA, “Global EV Outlook 2025 – Analysis - IEA,” Singapore, May 2025. Accessed: Oct. 13, 2025. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2025

[2] ENTSO-E, “Deployment of heavy-duty electric vehicles and their impact on the power system,” 2023. Accessed: May 07, 2025. [Online]. Available: https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/Publications/Position%20papers%20and%20reports/2023/231006_ENTSO-E_Position%20Paper_Deployment%20of%20Heavy-Duty%20EVs%20and%20Impact%20on%20the%20Power%20System.pdf

[3] IEEE Smart Grid, “Accommodating charging load due to high electric vehicle adoption and tackling grid Impacts: grid reinforcement vs smart charging,” 2023.

[4] N. S. Pearre and H. Ribberink, “Review of research on V2X technologies, strategies, and operations,” *Renewable and Sustainable Energy Reviews*, vol. 105, no. April 2018, pp. 61–70, May 2019, doi: 10.1016/j.rser.2019.01.047.

[5] “Fourth Greenhouse Gas Study 2020.” Accessed: Nov. 24, 2025. [Online]. Available: https://www.imo.org/en/ourwork/environment/pages/fourth-imo-greenhouse-gas-study-2020.aspx

[6] Christopher Hecht, Jan Figgener, and Dirk Uwe Sauer, “Protocols and Interfaces for EV Charging,” in *Next Generation Electrified Vehicles Optimised for the Infrastructure*, 2024.

[7] Vasileios Rizos and Patricia Urban, “Implementing the EU digital battery passport: Oporttunities and challenges for battery circularity ,” 2024. Accessed: Aug. 28, 2025. [Online]. Available: https://circulareconomy.europa.eu/platform/sites/default/files/2024-03/1qp5rxiZ-CEPS-InDepthAnalysis-2024-05_Implementing-the-EU-digital-battery-passport.pdf

[8] A. ur Rehman, H. M. Khalid, and S. M. Muyeen, “Grid-integrated solutions for sustainable EV charging: a comparative study of renewable energy and battery storage systems,” *Front Energy Res*, vol. 12, Sep. 2024, doi: 10.3389/fenrg.2024.1403883.

[9] M. Gilvanejad, H. Askarian Abyaneh, and K. Mazlumi, “Estimation of the overload-related outages in distribution networks considering the random nature of the electrical loads,” *IET Generation, Transmission & Distribution*, vol. 7, no. 8, pp. 855–865, Aug. 2013, doi: 10.1049/iet-gtd.2013.0085.

[10] A. Jenn and J. Highleyman, “Distribution grid impacts of electric vehicles: A California case study,” *iScience*, vol. 25, no. 1, p. 103686, Jan. 2022, doi: 10.1016/j.isci.2021.103686.

[11] P. Paudyal, S. Ghosh, S. Veda, D. Tiwari, and J. Desai, “EV hosting capacity analysis on distribution grids,” in *2021 IEEE Power & Energy Society General Meeting (PESGM)*, IEEE, Jul. 2021, pp. 1–5. doi: 10.1109/PESGM46819.2021.9638170.

[12] M. Kintner-Meyer *et al.*, “Electric vehicles at scale - phase II - distribution systems analysis,” Richland, WA (United States), Mar. 2022. doi: 10.2172/1882799.

[13] “Iberian blackout was first known caused by excessive voltage, report says | Reuters.” Accessed: Nov. 24, 2025. [Online]. Available: https://www.reuters.com/business/energy/iberian-blackout-was-first-over-voltage-caused-blackout-2025-10-03/?utm_source=chatgpt.com

[14] S. Salimon, G. Adepoju, I. Adebayo, H. Howlader, S. Ayanlade, and O. Adewuyi, “Impact of distributed generators penetration level on the power loss and voltage profile of radial distribution networks,” *Energies (Basel)*, vol. 16, no. 4, p. 1943, Feb. 2023, doi: 10.3390/en16041943.

[15] M. Tahir, M. E. Nassar, R. El-Shatshat, and M. M. A. Salama, “A review of Volt/Var control techniques in passive and active power distribution networks,” in *2016 IEEE Smart Energy Grid Engineering (SEGE)*, IEEE, Aug. 2016, pp. 57–63. doi: 10.1109/SEGE.2016.7589500.

[16] S. Deb, K. Tammi, K. Kalita, and P. Mahanta, “Impact of electric vehicle charging station load on distribution network,” *Energies (Basel)*, vol. 11, no. 1, p. 178, Jan. 2018, doi: 10.3390/en11010178.

[17] B. Azzopardi and Y. Gabdullin, “Impacts of Electric Vehicles Charging in Low-Voltage Distribution Networks: A Case Study in Malta,” *Energies (Basel)*, vol. 17, no. 2, p. 289, Jan. 2024, doi: 10.3390/en17020289.

[18] O. M. Hernández-Gómez and J. P. Abreu Vieira, “Probabilistic Assessment of the Impact of Electric Vehicle Fast Charging Stations Integration into MV Distribution Networks Considering Annual and Seasonal Time-Series Data,” *Energies (Basel)*, vol. 17, no. 18, p. 4624, Sep. 2024, doi: 10.3390/en17184624.

[19] K. N. Hasan, K. M. Muttaqi, P. Borboa, J. Scira, Z. Zhang, and M. Leishman, “Distribution network voltage analysis with data-driven electric vehicle load profiles,”

Sustainable Energy, Grids and Networks, vol. 36, p. 101216, Dec. 2023, doi: 10.1016/J.SEGAN.2023.101216.

[20] B. Azzopardi and Y. Gabdullin, "Impacts of Electric Vehicles Charging in Low-Voltage Distribution Networks: A Case Study in Malta," *Energies 2024, Vol. 17, Page 289*, vol. 17, no. 2, p. 289, Jan. 2024, doi: 10.3390/EN17020289.

[21] I. Nutkani, H. Toole, N. Fernando, and L. P. C. Andrew, "Impact of EV charging on electrical distribution network and mitigating solutions – A review," *IET Smart Grid*, vol. 7, no. 5, pp. 485–502, Oct. 2024, doi: 10.1049/STG2.12156.

[22] H. Sun *et al.*, "Review of Challenges and Research Opportunities for Voltage Control in Smart Grids," *IEEE Transactions on Power Systems*, vol. 34, no. 4, pp. 2790–2801, Jul. 2019, doi: 10.1109/TPWRS.2019.2897948.

[23] T. Bhattacharjee, M. Rajeshwari, and K. J. Kumar, "Electric Vehicle Charging and its Effects on the Power Distribution Network – A Review," *Power Research - A Journal of CPRI*, pp. 89–98, Sep. 2024, doi: 10.33686/pwj.v20i1.1170.

[24] Cindy P. Guzman *et al.*, "Deliverable D1.2 Impact of v2x in energy and power systems," 2023. Accessed: Mar. 12, 2024. [Online]. Available: https://cordis.europa.eu/project/id/101056765

[25] Y. G. Werkie, G. N. Nyakoe, and C. W. Wekesa, "Power System Voltage Stability Assessment and Control Strategies: State-of-the-Art Review," *Journal of Electrical and Computer Engineering*, vol. 2025, no. 1, Jan. 2025, doi: 10.1155/jece/6667482.

[26] T. Jain, K. Verma, and M. Bhadu, "N − 1 Security Criteria Based Integrated Deterministic and Probabilistic Framework for Composite Power System Reliability," *Journal of Electrical and Computer Engineering*, vol. 2024, pp. 1–21, Feb. 2024, doi: 10.1155/2024/5518874.

[27] N. Junnarkar, E. Jensen, X. Wu, S. Gumussoy, and M. Arcak, "Grouping of *N–1* Contingencies for Controller Synthesis: A Study for Power Line Failures," *IEEE Transactions on Power Systems*, vol. 40, no. 1, pp. 585–596, Jan. 2025, doi: 10.1109/TPWRS.2024.3393866.

[28] S. S. G. Acharige *et al.*, "Grid integration of electric vehicles - Impact assessment and remedial measures," *J Power Sources*, vol. 650, p. 236697, Sep. 2025, doi: 10.1016/j.jpowsour.2025.236697.

[29] S. Deb, K. Tammi, K. Kalita, and P. Mahanta, “Impact of Electric Vehicle Charging Station Load on Distribution Network,” *Energies (Basel)*, vol. 11, no. 1, p. 178, Jan. 2018, doi: 10.3390/en11010178.

[30] M. Ranjan and R. Shankar, “A literature survey on load frequency control considering renewable energy integration in power system: Recent trends and future prospects,” *J Energy Storage*, vol. 45, p. 103717, Jan. 2022, doi: 10.1016/j.est.2021.103717.

[31] Charalampos Ziras *et al.*, “Deliverable D2.2 Control strategies for V2X integration in buildings,” 2023. Accessed: Mar. 12, 2024. [Online]. Available: https://cordis.europa.eu/project/id/101056765

[32] Samuel Matias *et al.*, “V2X Integration in self-consumption energy management system,” 2023. Accessed: Mar. 15, 2024. [Online]. Available: https://orbit.dtu.dk/en/publications/v2x-integration-in-self-consumption-energy-management-system

[33] M. Müller, Y. Blume, and J. Reinhard, “Impact of behind-the-meter optimised bidirectional electric vehicles on the distribution grid load,” *Energy*, vol. 255, p. 124537, Sep. 2022, doi: 10.1016/j.energy.2022.124537.

[34] M. Safayatullah, M. T. Elrais, S. Ghosh, R. Rezaii, and I. Batarseh, “A Comprehensive Review of Power Converter Topologies and Control Methods for Electric Vehicle Fast Charging Applications,” *IEEE Access*, vol. 10, pp. 40753–40793, 2022, doi: 10.1109/ACCESS.2022.3166935.

[35] J. Yuan, L. Dorn-Gomba, A. D. Callegaro, J. Reimers, and A. Emadi, “A Review of Bidirectional On-Board Chargers for Electric Vehicles,” *IEEE Access*, vol. 9, pp. 51501–51518, 2021, doi: 10.1109/ACCESS.2021.3069448.

[36] S. Kim and F. Kang, “Hybrid battery charging system combining OBC with LDC for electric vehicles,” in *2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA)*, IEEE, May 2014, pp. 2260–2265. doi: 10.1109/IPEC.2014.6869904.

[37] M. Brenna, F. Foiadelli, C. Leone, and M. Longo, “Electric Vehicles Charging Technology Review and Optimal Size Estimation,” *Journal of Electrical Engineering & Technology*, vol. 15, no. 6, pp. 2539–2552, Nov. 2020, doi: 10.1007/s42835-020-00547-x.

[38] H. Kilicoglu and P. Tricoli, “Technical Review and Survey of Future Trends of Power Converters for Fast-Charging Stations of Electric Vehicles,” *Energies (Basel)*, vol. 16, no. 13, p. 5204, Jul. 2023, doi: 10.3390/en16135204.

[39] S. Panchanathan *et al.*, “A Comprehensive Review of the Bidirectional Converter Topologies for the Vehicle-to-Grid System,” *Energies (Basel)*, vol. 16, no. 5, p. 2503, Mar. 2023, doi: 10.3390/en16052503.

[40] M. Schweizer and J. W. Kolar, “Design and Implementation of a Highly Efficient Three-Level T-Type Converter for Low-Voltage Applications,” *IEEE Trans Power Electron*, vol. 28, no. 2, pp. 899–907, Feb. 2013, doi: 10.1109/TPEL.2012.2203151.

[41] A. Sheir, M. Z. Youssef, and M. Orabi, “A Novel Bidirectional T-Type Multilevel Inverter for Electric Vehicle Applications,” *IEEE Trans Power Electron*, vol. 34, no. 7, pp. 6648–6658, Jul. 2019, doi: 10.1109/TPEL.2018.2871624.

[42] F. E. U. Reis, R. P. Torrico-Bascope, F. L. Tofoli, and L. D. Santos Bezerra, “Bidirectional Three-Level Stacked Neutral-Point-Clamped Converter for Electric Vehicle Charging Stations,” *IEEE Access*, vol. 8, pp. 37565–37577, 2020, doi: 10.1109/ACCESS.2020.2976003.

[43] S. Rivera, B. Wu, S. Kouro, V. Yaramasu, and J. Wang, “Electric Vehicle Charging Station Using a Neutral Point Clamped Converter With Bipolar DC Bus,” *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 1999–2009, Apr. 2015, doi: 10.1109/TIE.2014.2348937.

[44] H.-U. Go, S.-H. Lee, M.-S. Kim, G. Zhou, S.-J. Park, and Y. Wang, “Three-phase VIENNA Rectifier Interval Control Strategy to Improve Light Load Performance,” *IEEE J Emerg Sel Top Power Electron*, pp. 1–1, 2025, doi: 10.1109/JESTPE.2025.3570686.

[45] B. K. Karunakar Rao, “Application of Power Converters in EV Charging Infrastructure,” in *Electric Vehicle Charging Infrastructures and its Challenges*, 2025, pp. 263–307.

[46] D. Zakzewski, R. Resalayyan, and A. Khaligh, “Hybrid Neutral Point Clamped Converter: Review and Comparison to Traditional Topologies,” *IEEE Transactions on Transportation Electrification*, vol. 10, no. 3, pp. 6087–6099, Sep. 2024, doi: 10.1109/TTE.2023.3348241.

[47] L. Jorge, H. Concepcion, M. A. Arjona, M. Lesedi, and C. Ambrish, “Performance Evaluation of an Active Neutral-Point-Clamped Multilevel Converter for Active Filtering

in G2V-V2G and V2H Applications," *IEEE Access*, vol. 10, pp. 41607–41621, 2022, doi: 10.1109/ACCESS.2022.3167694.

[48] R. Kallelapu, S. Peddapati, and S. V. K. Naresh, "A Family of Nonisolated Quadratic Buck-Boost Bidirectional Converters With Reduced Current Ripple for EV Charger Applications," *IEEE Trans Power Electron*, vol. 40, no. 12, pp. 18407–18420, Dec. 2025, doi: 10.1109/TPEL.2025.3592387.

[49] D. Zhang, D. Cao, J. Huber, J. Everts, and J. W. Kolar, "Nonisolated Three-Phase Current DC-Link Buck–Boost EV Charger With Virtual Output Midpoint Grounding and Ground Current Control," *IEEE Transactions on Transportation Electrification*, vol. 10, no. 1, pp. 1398–1413, Mar. 2024, doi: 10.1109/TTE.2023.3282978.

[50] D. Das, N. Weise, K. Basu, R. Baranwal, and N. Mohan, "A Bidirectional Soft-Switched DAB-Based Single-Stage Three-Phase AC–DC Converter for V2G Application," *IEEE Transactions on Transportation Electrification*, vol. 5, no. 1, pp. 186–199, Mar. 2019, doi: 10.1109/TTE.2018.2886455.

[51] Y. Park, S. Chakraborty, and A. Khaligh, "DAB Converter for EV Onboard Chargers Using Bare-Die SiC MOSFETs and Leakage-Integrated Planar Transformer," *IEEE Transactions on Transportation Electrification*, vol. 8, no. 1, pp. 209–224, Mar. 2022, doi: 10.1109/TTE.2021.3121172.

[52] Y. Xuan, X. Yang, W. Chen, T. Liu, and X. Hao, "A Novel Three-Level *CLLC* Resonant DC–DC Converter for Bidirectional EV Charger in DC Microgrids," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 3, pp. 2334–2344, Mar. 2021, doi: 10.1109/TIE.2020.2972446.

[53] P. He and A. Khaligh, "Comprehensive Analyses and Comparison of 1 kW Isolated DC–DC Converters for Bidirectional EV Charging Systems," *IEEE Transactions on Transportation Electrification*, vol. 3, no. 1, pp. 147–156, Mar. 2017, doi: 10.1109/TTE.2016.2630927.

[54] M. Troviano and G. G. Oggier, "Reactive Power Reduction in Triple Active Bridge Converters for Hybrid Energy Storage Systems in Electric Vehicle Applications," *IEEE Transactions on Transportation Electrification*, vol. 11, no. 5, pp. 12572–12583, Oct. 2025, doi: 10.1109/TTE.2025.3592078.

[55] S. Zou, J. Lu, and A. Khaligh, “Modelling and control of a triple-active-bridge converter,” *IET Power Electronics*, vol. 13, no. 5, pp. 961–969, Apr. 2020, doi: 10.1049/iet-pel.2019.0920.

[56] X. Li, H. Ma, S. Ren, J. Yi, S. Lu, and Q. Feng, “A Novel LCL Resonant Converter With Inherent CC-CV Output for On-Board Chargers of Plug-In Electric Vehicles,” *IEEE Trans Power Electron*, vol. 38, no. 4, pp. 4212–4217, Apr. 2023, doi: 10.1109/TPEL.2022.3229025.

[57] J. Zeng, G. Zhang, S. S. Yu, B. Zhang, and Y. Zhang, “LLC resonant converter topologies and industrial applications — A review,” *Chinese Journal of Electrical Engineering*, vol. 6, no. 3, pp. 73–84, Sep. 2020, doi: 10.23919/CJEE.2020.000021.

[58] N. T. Milas and E. C. Tatakis, “Fast Battery Cell Voltage Equalizer Based on the Bidirectional Flyback Converter,” *IEEE Transactions on Transportation Electrification*, vol. 9, no. 4, pp. 4922–4940, Dec. 2023, doi: 10.1109/TTE.2022.3186520.

[59] G. Sha *et al.*, “Research on Multi-Port DC-DC Converter Based on Modular Multilevel Converter and Cascaded H Bridges for MVDC Applications,” *IEEE Access*, vol. 9, pp. 95006–95022, 2021, doi: 10.1109/ACCESS.2021.3072161.

[60] S. Sarkar and A. Das, “An Isolated Single Input-Multiple Output DC–DC Modular Multilevel Converter for Fast Electric Vehicle Charging,” *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, vol. 4, no. 1, pp. 178–187, Jan. 2023, doi: 10.1109/JESTIE.2022.3221006.

[61] M. Abarzadeh, W. A. Khan, N. Weise, K. Al-Haddad, and A. M. EL-Refaie, “A New Configuration of Paralleled Modular ANPC Multilevel Converter Controlled by an Improved Modulation Method for 1 MHz, 1 MW EV Charger,” *IEEE Trans Ind Appl*, vol. 57, no. 3, pp. 3164–3178, May 2021, doi: 10.1109/TIA.2020.3019778.

[62] G. Iannaccone, C. Sbrana, I. Morelli, and S. Strangio, “Power Electronics Based on Wide-Bandgap Semiconductors: Opportunities and Challenges,” *IEEE Access*, vol. 9, pp. 139446–139456, 2021, doi: 10.1109/ACCESS.2021.3118897.

[63] J. Saha, N. Kumar, and S. K. Panda, “A Futuristic Silicon-Carbide (SiC)-Based Electric-Vehicle Fast Charging/Discharging (FC/dC) Station,” *IEEE J Emerg Sel Top Power Electron*, vol. 11, no. 3, pp. 2904–2917, Jun. 2023, doi: 10.1109/JESTPE.2022.3223417.

[64] Mouser Electronics, "Implementing Fast DC Chargers with Silicon Carbide MOSFETs | Benc." Accessed: Oct. 04, 2025. [Online]. Available: https://eu.mouser.com/blog/implementing-fast-dcchargers-sic-mosfets

[65] D. N. Dalal *et al.*, "Demonstration of a 10 kV SiC MOSFET based Medium Voltage Power Stack," in *2020 IEEE Applied Power Electronics Conference and Exposition (APEC)*, IEEE, Mar. 2020, pp. 2751–2757. doi: 10.1109/APEC39645.2020.9124441.

[66] G. Liu *et al.*, "Comparison of SiC MOSFETs and GaN HEMTs based high-efficiency high-power-density 7.2kW EV battery chargers," in *2017 IEEE 5th Workshop on Wide Bandgap Power Devices and Applications (WiPDA)*, IEEE, Oct. 2017, pp. 391–397. doi: 10.1109/WiPDA.2017.8170579.

[67] M. H. Wong, O. Bierwagen, R. J. Kaplar, and H. Umezawa, "Ultrawide-bandgap semiconductors: An overview," *J Mater Res*, vol. 36, no. 23, pp. 4601–4615, Dec. 2021, doi: 10.1557/S43578-021-00458-1/TABLES/1.

[68] M. Leibl, G. Ortiz, and J. W. Kolar, "Design and Experimental Analysis of a Medium-Frequency Transformer for Solid-State Transformer Applications," *IEEE J Emerg Sel Top Power Electron*, vol. 5, no. 1, pp. 110–123, Mar. 2017, doi: 10.1109/JESTPE.2016.2623679.

[69] S. Balci, I. Sefa, and M. B. Bayram, "Core material investigation of medium-frequency power transformers," *16th International Power Electronics and Motion Control Conference and Exposition, PEMC 2014*, pp. 861–866, Dec. 2014, doi: 10.1109/EPEPEMC.2014.6980606.

[70] M. Neaimeh and P. B. Andersen, "Mind the gap- open communication protocols for vehicle grid integration," *Energy Informatics*, vol. 3, no. 1, p. 1, Dec. 2020, doi: 10.1186/s42162-020-0103-1.

[71] Spirii, "OICP - Open Intercharge protocol," Spirii. Accessed: Sep. 27, 2025. [Online]. Available: https://www.spirii.com/en/glossary/open-intercharge-protocol

[72] Alexios Lekidis, Ioannis Papadopoulos, Hugo Morais, and Ana Rita Nunes, "Deliverable D5.2: Standardization gap analysis for new V2X related Business Models," 2023. Accessed: Sep. 27, 2025. [Online]. Available: https://ev4eu.eu/wp-content/uploads/2023/11/Attachment_0-2023-11-03T002755.860.pdf

[73] C. Hecht, J. Figgener, and D. U. Sauer, “Protocols and Interfaces for EV Charging,” *SpringerBriefs in Applied Sciences and Technology*, vol. Part F2040, pp. 77–89, 2024, doi: 10.1007/978-3-031-47683-9_7/TABLES/3.

[74] eng, “The EU Battery Passport: Requirements, Timelines and Benefits - Engineering Industries eXcellence.” Accessed: Sep. 27, 2025. [Online]. Available: https://www.indx.com/en/posts/the-eu-battery-passport-requirements-timelines-and-benefits

[75] Circularise, “EU battery passport regulation requirements,” Circularise Web. Accessed: Sep. 27, 2025. [Online]. Available: https://www.circularise.com/blogs/eu-battery-passport-regulation-requirements

[76] Global Battery Alliance, “2024 Battery Passport Pilots,” GBA Web. Accessed: Sep. 27, 2025. [Online]. Available: https://www.globalbattery.org/battery-passport-mvp-pilots/

[77] electrek, “Take a look at Tesla’s first battery passport proof-of-concept | Electrek,” electrek Web. Accessed: Sep. 27, 2025. [Online]. Available: https://electrek.co/2023/01/18/tesla-first-battery-passport-proof-of-concept/

[78] LG, “LG Energy Solution Unlocking More Sustainable Battery Value Chain with World’s First Battery Passport – LG Energy Solution,” LG web. Accessed: Sep. 27, 2025. [Online]. Available: https://news.lgensol.com/company-news/supplementary-stories/1406/

[79] Climateworks Foundation, “Digital Battery Passports: An Enabler for Sustainable and Circular Battery Management,” 2023.

[80] Jacqueline Holman, “Battery Pass consortium analysis reveals benefits, challenges of European Battery Passport | S&P Global,” spglobal. Accessed: Sep. 27, 2025. [Online]. Available: https://www.spglobal.com/commodity-insights/en/news-research/latest-news/metals/041124-battery-pass-consortium-analysis-reveals-benefits-challenges-of-european-battery-passport

[81] M. Gianvincenzi, M. Marconi, E. M. Mosconi, and F. Tola, “A Standardized Data Model for the Battery Passport: Paving the Way for Sustainable Battery Management,” *Procedia CIRP*, vol. 122, pp. 103–108, Jan. 2024, doi: 10.1016/j.procir.2024.01.014.

[82] C. A. Rufino Júnior *et al.*, “Towards to Battery Digital Passport: Reviewing Regulations and Standards for Second-Life Batteries,” *Batteries 2024, Vol. 10, Page 115*, vol. 10, no. 4, p. 115, Mar. 2024, doi: 10.3390/BATTERIES10040115.

[83] European Union, “Regulation - 2023/1542 - EN - EUR-Lex.” Accessed: Sep. 27, 2025. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2023/1542/oj/eng

[84] Intertek, “EU Battery Regulation explained.” Accessed: Sep. 27, 2025. [Online]. Available: https://www.intertek.com/blog/2023/08-17-battery-regulation/

[85] Sato Europe, “New Battery Passport Standards Released and What Businesses Need to Know.” Accessed: Sep. 27, 2025. [Online]. Available: https://www.satoeurope.com/insight/new-battery-passport-standards-released-and-what-businesses-need-to-know/142

[86] M. Terkes, A. Demirci, E. Gokalp, and U. Cali, “Battery Passport for Second-Life Batteries: Potential Applications and Challenges,” *IEEE Access*, vol. 12, pp. 128424–128467, 2024, doi: 10.1109/ACCESS.2024.3450790.