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Review Article

Advancements in DC Fast Charging for Electric Vehicles: A Review of Architectures, Smart Charging Strategies, and Standards

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***Abstract* - *Since the growth of Electric Vehicles (EVs) continues to rapidly gain momentum in the world, there has been a sharp increase in the demand for efficient and smart DC fast charging structures. This paper provides a comprehensive overview of the technologies that contribute to DC fast charging in modern times: system structure and charging standards, as well as the direction of smart charging. In this article, the authors have discussed the choice of different charges, such as wired connection-based charging, battery swapping, and wireless charging, and outlined on-board and off-board chargers in terms of their functions in the existing EV systems. Some of the prominent technical aspects are discussed, like the AC/DC conversion scheme and other DC/DC converter topologies, with emphasis being laid on the isolated or non-isolated design. The idea of distributed energy resources, i.e., solar power and battery storage systems, is brought into discussion on the potential of these resources to facilitate providing grid stability and environmental sustainability. Particular attention is paid to the Open Charge Point Protocol (OCPP), one of the key enablers of the smart charging infrastructure. Starting from the beginning of OCPP to the publication of version 2.1 in 2025, the review describes the history of the development of OCPP as an interoperability enhancer, remote access, load control, and coordinated communication between EVs, charging stations, and energy networks. By consolidating advancements in both technology and standardization, this paper contributes to the growing body of knowledge guiding the evolution of next-generation Electric Vehicle (EV) charging systems.*

Keywords* - *AC/DC rectifier, DC/DC converters, Smart charging, OCPP.

1. Introduction

The transportation sector is a key contributor to Global Greenhouse Gas (GHG) emissions due to its heavy reliance on fossil fuels [1]. According to the Global Energy Review 2025 by the International Energy Agency (IEA), global energy-related CO_2 emissions reached a record high of 37.8 GT in 2024, an increase of 0.8% from the previous year. This contributed to atmospheric CO_2 concentrations rising to 422.5 ppm, approximately 50% above pre-industrial levels [2]. Among the energy-consuming sectors, road transport continues to play a dominant role in these emissions. Electric Vehicles (EVs) have appeared as a key strategy for reducing the carbon footprint of the transportation sector. Global EV adoption is accelerating rapidly, with over 17 million electric cars sold in 2023, accounting for around 20% of all new car sales worldwide. This surge in EV deployment led to an 8% increase in electricity demand in the transport sector during 2024 [3], intensifying the need for scalable, efficient, and sustainable EV charging infrastructure. To support this growth, the development of accessible and robust charging networks is crucial. As of 2023, nearly 4 million publicly accessible EV charging points were deployed globally. This number is expected to exceed 15 million by 2030 and reach approximately 25 million by 2035, representing a sixfold increase. The expansion of fast-charging stations has been especially notable, with the number of public fast chargers growing by 55% in 2023 alone, now constituting more than 35% of global public charging infrastructure. China leads this development, hosting over 85% of the world's fast chargers and about 60% of slow chargers, followed by significant infrastructure growth in North America and Europe [4, 5].

EV charging technologies are typically categorized into three types: conductive (wired) charging, wireless charging, and battery swapping [6]. As shown in Figure 1, conductive charging includes onboard and off-board systems; the former allows charging via standard sockets but is limited by lower power and longer charging times, while the latter supports higher power levels and enables fast charging through external stations [7]. Wireless charging, based on electromagnetic induction or resonance, provides a cable-free interface and supports both static and dynamic applications, but remains challenged by system alignment, efficiency, and deployment cost [8]. Battery swapping enables near-instant battery replacement but faces barriers related to battery standardization, ownership models, and station complexity [9].

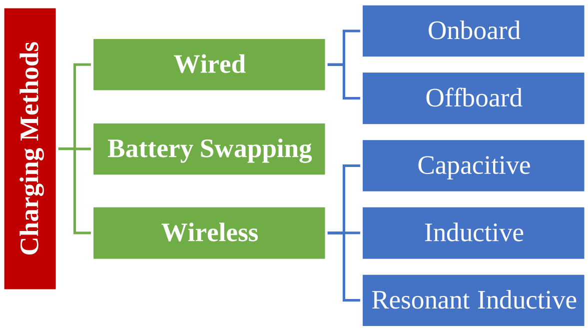


Fig. 1 Charging methods

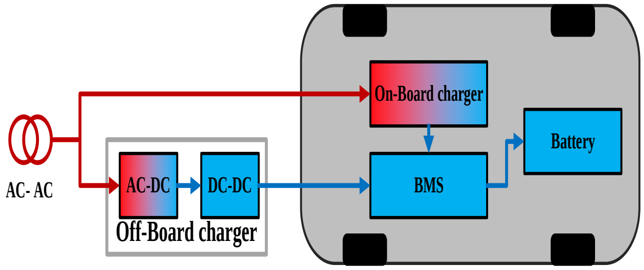


Fig. 2 Wired onboard and off-board chargers

On-board chargers offer the advantage of convenient charging at any electrical outlet and avoid battery overheating directly, operating with low power output and utilizing the J1172 pilot signal [10]. Nevertheless, they have low charging rates, reduced power transmission, and add to the weight of the vehicle. Their architecture requires adding other charging elements that may affect their portability, and their communication specifications are not the best. Moreover, the on-board Battery Management System (BMS) depends on the given charging station phase configuration, supply voltage, and current capacity, as shown in Figure 2. On the contrary, off-board chargers offer higher charges because of their high power output, lighten the vehicle load, and support more sophisticated BMS [11]. However, they have reduced capabilities because of the capacity of the battery to take charge, and they bring more complexity and cost, and also, there are possible heating issues with the battery. The availability of compatible charging stations also limits access to off-board charging. It is also very expensive and complicated to integrate the BMS with these stations [12]. The addition of renewable energy sources, particularly solar photovoltaic (PV), into EV charging systems has become increasingly attractive due to the potential for a zero-emission energy supply [13]. By the end of 2024, global solar PV capacity exceeded 1,700 GW, reflecting its growing role in powering transport and reducing dependence on grid electricity derived from fossil fuels. Challenges, advanced energy management systems, real-time control, and power electronic solutions are needed to guarantee reliability and efficiency[14, 15]. In addition, the study of new control algorithms and energy management strategies can achieve the high efficiency and reliability of photovoltaic-fast charging stations [16]. Such improvements would enable the stations to be adjusted to dynamically changing energy supply and offer a seamless charging experience to EV users [17]. This review aims to comprehensively examine recent developments in electric vehicle charging technologies, with a particular emphasis on fast charging architectures, wireless power transfer systems, Vehicle-to-Grid (V2G) capabilities, and renewable-powered charging infrastructure. The paper also discusses regional deployment trends, policy implications, and emerging research directions shaping the future of EV charging systems.

2. State of the Art and Research Gap

Although there has been considerable technological development in EV charging systems, comparatively a limited number of review articles combine charger hardware systems, smart charging plans, renewable energy incorporation, and evolving communication benchmarks especially the current version of Open Charge Point Protocol (OCPP 2.1, 2025). These components have been studied in the majority of existing reviews separately, without taking an integrated point of view, particularly within the framework of the high-power DC fast charging structure. With the aim of defining the current state of the literature, Table 1 provides a systematized comparison of high-profile review articles on six key dimensions, which are charger architectures, DC fast charging, integrated Distributed Energy Resource (DER), smart charging strategies, the adoption of OCPP 2.1, and the compliance with international standards in charging.

Table 1. Summary of existing review studies and coverage scope

Existing work	Publication year	Charger a Architectures	Focused on DC fast charging	DER	Smart charging	OCPP 2.1	Charging standards
[18]	2020	☒	☒	☑	☑	☒	☒
[19]	2022	☒	☑	☑	☑	☒	☑
[20]	2022	☑	☒	☒	☑	☒	☑
[21]	2022	☒	☒	☑	☑	2.0.1	☒
[22]	2022	☑	☒	☑	☑	☑	☑
[23]	2023	☑	☑	☑	☑	☒	☒

[24]	2023	☑	☑	☑	☒	☒	☑
[25]	2023	☑	☑	☑	☑	☒	☑
[26]	2023	☑	☑	☑	☒	☒	☑
[27]	2023	☒	☒	☑	☑	☒	☒
[12]	2024	☑	☑	☑	☒	☒	☑
[28]	2024	☑	☑	☑	☒	☒	☑
[29]	2024	☑	☑	☑	☑	☒	☑
[30]	2024	☑	☑	☑	☑	☑	☑
[31]	2024	☒	☒	☑	☑	☒	☒
[32]	2024	☒	☒	☑	☑	☒	☒
Present work	--	☑	☑	☑	☑	2.1	☑

The hardware architecture of chargers, especially for converters such as AC/DC and DC/DC topologies, has undergone significant development. With regard to DC fast charging systems, recent studies focus on the advancement of efficiency, reliability, and compactness.

However, reviews are often restricted to a particular type of converter or case studies, in which different results are compared case-by-case without an overall comparative analysis. DC fast charging, which is crucial for decreasing the charging times and supporting the EV idea in commercial and public transport sectors, has been studied in various studies. Yet, total analyses taking different technological methods, such as isolated vs. non-isolated converters and their different strengths into account, are limited.

Integration of Distributed Energy Resources (DERs), for example, renewable energy sources, batteries, and microgrid systems, is increasingly being identified as important for sustainability and grid resilience. Reviews generally address DER integration without reference to charger architectures and smart charging controls in the mix, and leave gaps in their effectiveness when combined for grid performance and effective energy management.

Smart charging strategies are key in the optimization of power flows, load management of the grid, and in real-time interaction of vehicles, charging stations, and the rest of the power grid. Although there are a few reviews on smart charging, because they do not consider the underlying hardware constraints or integration in the context of DER systems in any detail, the practical applicability of the results is limited. Additionally, standardized communication protocols, specifically the OCPP, form the basis for interoperability and sophisticated management of EV charging networks. The development of OCPP, particularly the additions of the latest version 2.1, with the addition of better cyber security, scalability and bi-directional communication, has been relatively little examined in the context of charger architectures and smart charging methodologies. Finally, compliance with internationally recognised standards for charging is assured, enabling interoperability, safety, and wider acceptance of EV chargers. While many reviews take some recognition of charging standards, for the most part, there is little substantive analysis about the practical implications of charging standards when it comes to infrastructure deployment or regulatory harmonization.

Given these identified gaps, this review provides the following original contributions:

- Extended Analysis of the High-Power DC Fast Charging Topics: A non-arbitrary evaluation of the latest advances in isolated and non-isolated AC/DC and DC/DC converter architectures and their respective comparative advantages, shortcomings, and best application cases.
- Integration of Smart Charging Strategies and Distributed Energy Resources: Critical Evaluation of state-of-the-art Smart Charging Techniques in combination with DER Systems: Control algorithms, energy management strategies, and practical implications for grid flexibility, sustainability, and renewable energy integration.
- Clear Dissection of the Development and Effect of OCPP 2.1 (2025): This will involve a critical analysis of how OCPP has evolved over time, and on what elements have been implemented in the 2.1 version to improve it over previous versions. The special focus is made on the protocol's advancement, operating in security, scalability, and intelligent management potential of the charging system in the future.

This review will offer a denser and updated reflection by covering such interrelated dimensions charger architecture, fast charging technologies, renewable energy integration, smart charging strategies, communication standards, and regulatory frameworks. It can be a valuable asset to researchers, policymakers, and industry stakeholders who want to create and execute efficient, scalable, and sustainable EV charging solutions, thus hastening the process of achieving an e-mobile world worldwide.

3. Enabling Standards of DC Fast Charging

International standards bodies have created a comprehensive framework to enable fast charging of EVs in a safe manner [28]. Standards like IEC 60038 define standard voltages, and IEC 62196 defines requirements for AC charging elements, including connectors, cables, and communication between AC charging sections [33, 34]. SAE J1772 is the American standard for Level 1 and Level 2 AC charging in North America, providing both safety and compatibility specifications when connecting to a charging station or outlet. These standards play a crucial role in promoting the widespread adoption of EVs by facilitating interoperability and addressing safety concerns[30].

DC charging technology, as opposed to AC charging, transmits the charge directly from the DC charging station to the battery, eliminating the requirement for an onboard AC-DC converter [35]. This enables charging the EVs on a greatly increased power set, as it does not require the carrier to adjust the EV [36]. This is why the DC charging system has attracted so much attention, and such a network of DC fast charging sites is commonly implemented parallel to major highways to enable long-distance driving [37]. Based on this note, several studies have been developed, which seek short charging times for EV batteries and high-throughput charging stations so that it is possible to minimize the number of chargers to be allocated in each charging location [38-40]. The sheer number of EVs it will have to charge and the varying requirements passed down by the manufacturers now present a challenge for researchers and charger developers. This prompted different regulators to set different standards for the same charging process, ensuring that they could be used opposite one another and would be safe to use.

A unified standard charging protocol was similarly proposed by the International Electrotechnical Commission (IEC), where it was divided into three AC modes and 1 DC mode, which provide 400 kW charging power [45]. On the other hand, the Society of Automotive Engineers (SAE) in North America offers classes for four levels of chargers, with two classes for AC charging and the remaining two for DC charging. DC Level 1: 40 kW DC Level 2: 100 kW China's national standards (GB) have also established the GB/T 20234 series for EV charging infrastructure. The Alternating Current (AC) charging standard (GB/T 20234.2) supports AC charging at a 22kW level and the rest at 43–100kW level, while the maximum DC charging standard (GB/T 20234.3) supports 250 kW. The CHAdeMO, co-developed by Japanese manufacturers including Nissan and Mitsubishi, has since become the most popular fast-charging standard in the world.

Table 2. Summary of the standards for DC fast charging

Standard	Category	Voltage (V)	Current (A)	Power (kW)
IEC - 62196	MODE4	1000	400	400
SAE J1772	DC LEVEL1	500	80	40
	DC LEVEL2	500	200	100
GB/T - 20234.3 -2015	DC	1000	250	250
CHAdeMO	1.0	500	125	63
	1.2	500	400	200
	2.0	1000	400	400
	3.0	833	600	500

Table 3. EVs of 2025 – battery and charging specifications

Manufacturer	Model (2025)	Range (km)	Battery Capacity (kWh)	Battery Voltage (V)	DC Charging Power (kW)
Tesla	Cybertruck	523	123	800	250
Rivian	R1T	644	168	800	200
Lucid	Air	839	118	924	300
Chevrolet	Silverado EV	740	200	800	350
GMC	Hummer EV SUV	483	246.8	800	300
Hyundai	Ioniq 6	515	84	800	235
Kia	EV9	512	99.8	800	235
Ford	Mustang Mach-E	515	98	400	150
Mercedes-Benz	EQS Sedan	730	107.8	396	200
BMW	i7	625	105.7	400	195
Audi	Q8 e-tron	578	114	400	170
Porsche	Taycan	634	105	800	320
Xiaomi	SU7	800	101	800	300
BYD	Sea Lion 7	502	91.3	800	230

A summary of the standards for DC fast charging is presented in Table 2. As exemplified in Table 3, contemporary EVs demonstrate extended driving ranges reaching up to 839 km (Lucid Air) [41], with several models already surpassing the 640 km mark (e.g., Rivian R1T, Chevrolet Silverado EV)[42, 43]. This reflects a trend towards longer-range EVs, with even greater distances expected in future models. Mirroring this progress, manufacturers are increasing battery capacity and adopting 800V systems, as seen in models like the Tesla Cybertruck and Hyundai Ioniq 6, to minimize charging times and energy loss during rapid charging [44]. Furthermore, advancements in charging technology enable higher power outputs, with chargers like the one in the Chevrolet Silverado EV capable of delivering up to 350 kW, significantly reducing refueling time for EVs with substantial battery capacities. However, the transition to this advanced 800V charging infrastructure, facilitating ultra-fast DC charging, is accompanied by significant technological hurdles.

4. The Architecture of DC Fast Chargers

DC fast chargers for EVs are generally made up of three main stages, as illustrated in Figure 3. It starts with an AC-AC stage where a low-frequency transformer converts medium voltage from the grid to low voltage for the LVDC while providing galvanic isolation. The second step involves the conversion of AC–DC, where the alternating voltage is transformed with power electronics circuits into direct current [45]. Yet, for demanding high-power charging applications, this step has disadvantages, for example, the generation of unwanted harmonics. It also requires advanced protection devices and control strategies, which often include a wer factor corrector [46]. Lastly, the DC-DC conversion is involved in adjusting the DC voltage to the level required for charging the EV battery via power electronics [47]. At this first stage, galvanic isolation is not required because it is already taken care of by the transformer [48].

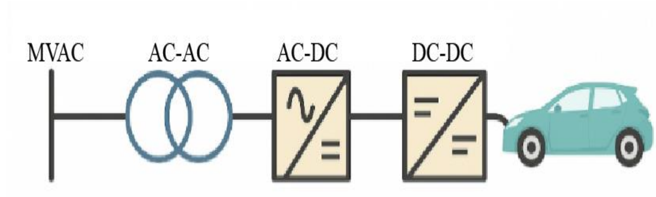


Fig. 3 The architecture of a DC fast charger

4.1. AC/DC Rectification Stage

AC/DC converters rectify the alternating voltage wave supplied by the power grid into direct current. In this step, a power factor corrector is usually included. [49, 50]. There are two types of AC/DC converters: unidirectional and bidirectional, as shown in Figure 4, which also presents the advantages and disadvantages of each type. Unidirectional converters, such as the Vienna rectifier with a T-type topology [51-53], are widely used in fast chargers. Bidirectional converters include three-phase Pulse Width Modulation (PWM) rectifiers [54, 55], Neutral Point Clamped (NPC) rectifiers [56, 57], and Cascaded H-Bridge rectifiers [58]. Figure 5 illustrates several common AC-DC converter configurations, including the Vienna, NPC, Cascaded H-Bridge, and T-type topologies.

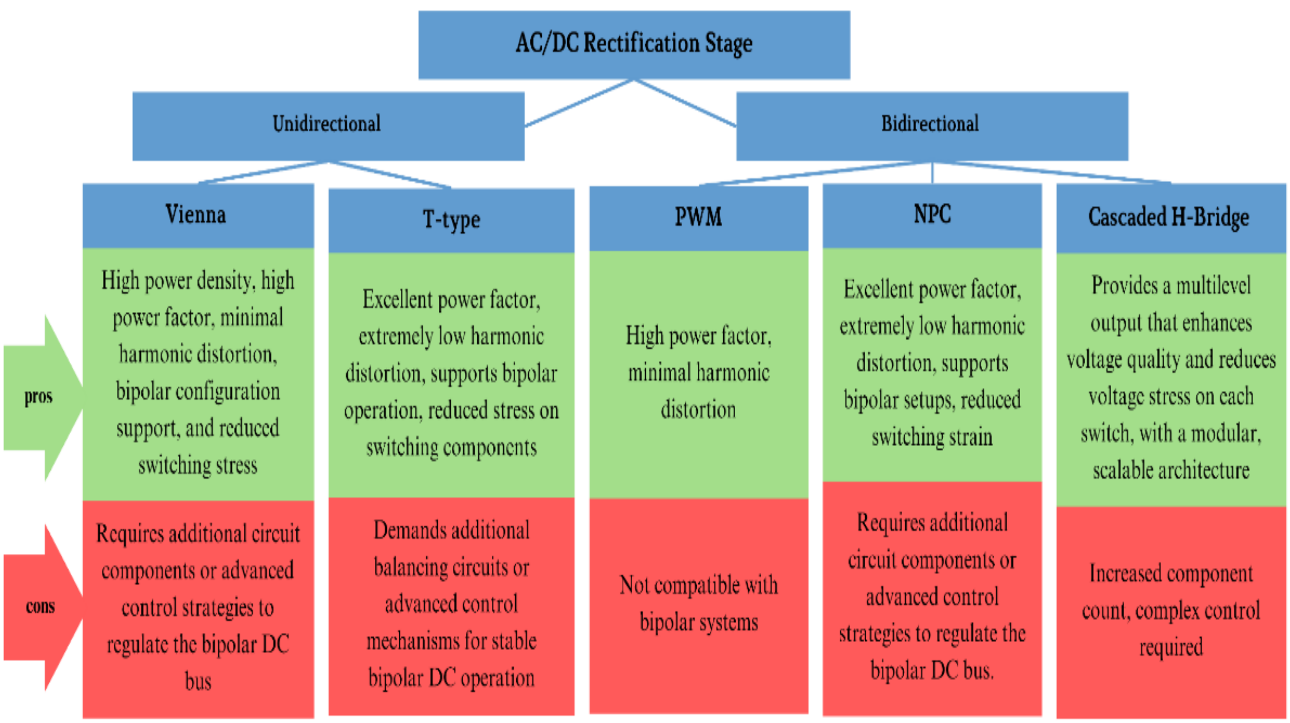
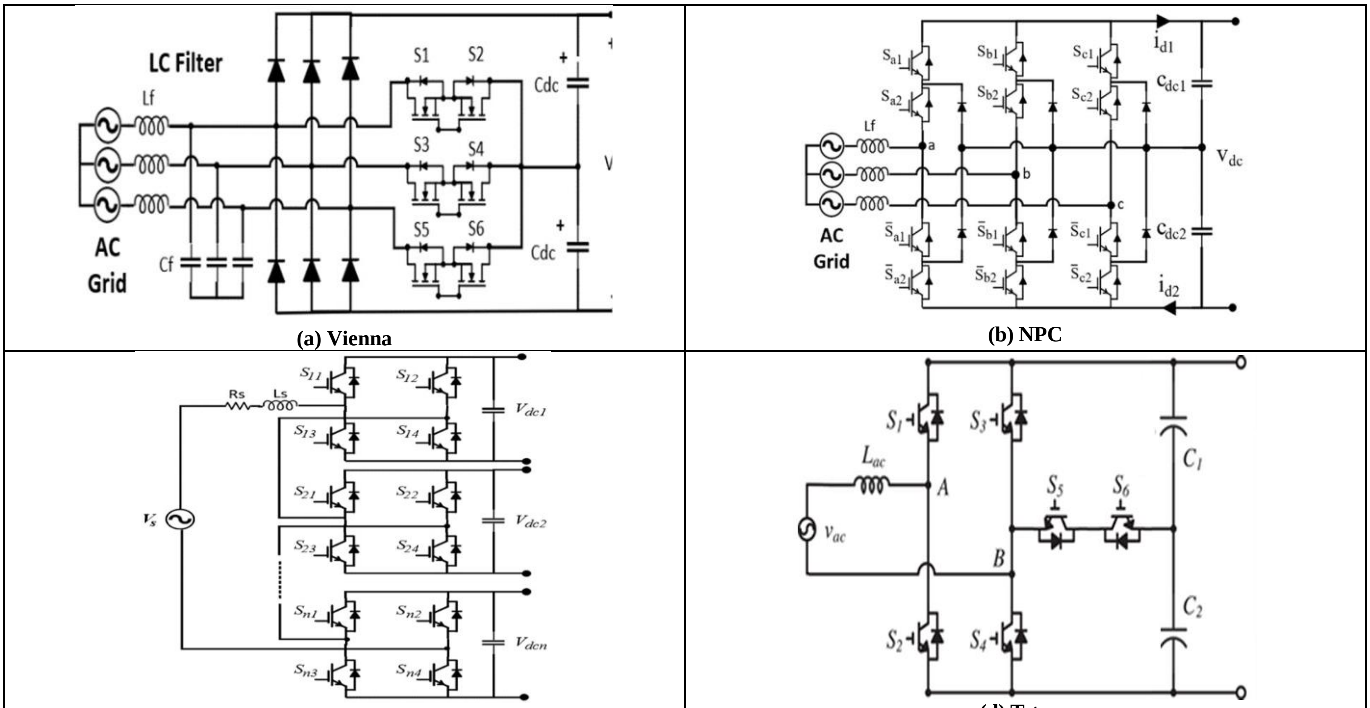


Fig. 4 Classification of AC/DC rectification stage



(a) Vienna (b) NPC (c)CHB (d) T-type

Fig. 5 AC-DC converter configurations: (a) Vienna, (b) NPC, (c) CHB, and (d) T-type.

4.2. DC-DC Converters

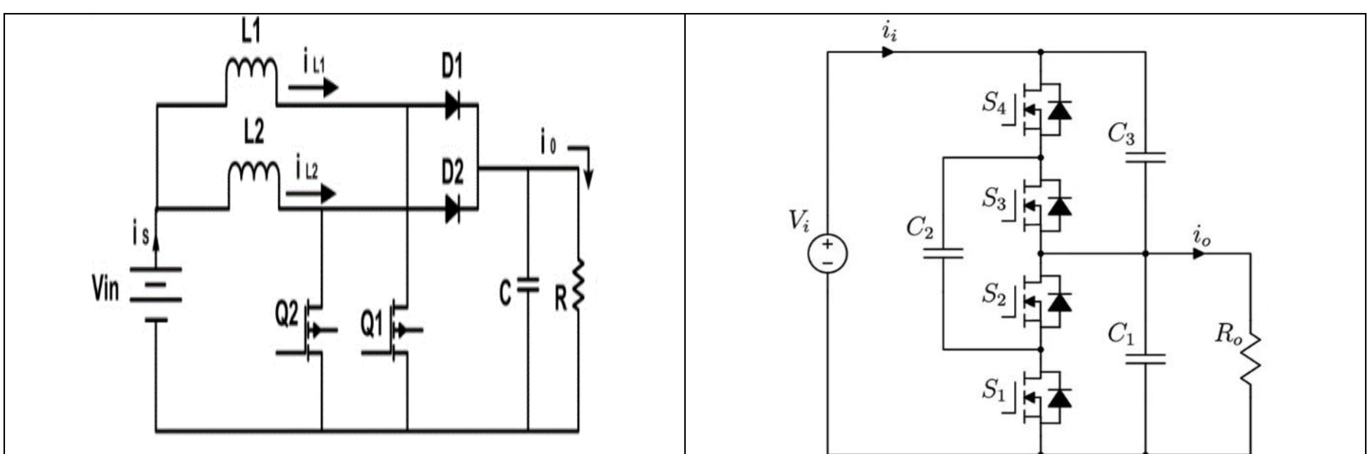
Most currently available Electric Vehicle (EV) battery chargers are designed for unidirectional energy flow from the Grid To the Vehicle (G2V).

These chargers have simpler architectures compared to bidirectional chargers, which offer additional benefits by enabling reverse energy flow (V2X). The two types of DC-DC converters are isolated and non-isolated.

4.2.1. Non-Isolated DC/DC Converters

Non-isolated DC/DC converters, lacking galvanic isolation, have no magnetic barrier to block direct current flow to the secondary side. They are compact, efficient, and simple in design, without isolation transformers. Common types include Ćuk, Switched Capacitor, Cascaded, and Interleaved converters (see Figure 6) [59-62] Their advantages include simplicity, lower losses, and improved efficiency due to the absence of isolation transformers, as well as enhanced thermal distribution, smaller filter sizes, and reduced current ripple in advanced designs.

However, these converters face limitations such as voltage-balance challenges in certain topologies and the potential for DC-link voltage ripple when multiple systems operate simultaneously.



(a)Interleaved converter (b)Switched capacitor converter

Fig. 6 Non-isolated converters: (a) Interleaved converter, and (b) Switched capacitor converter.

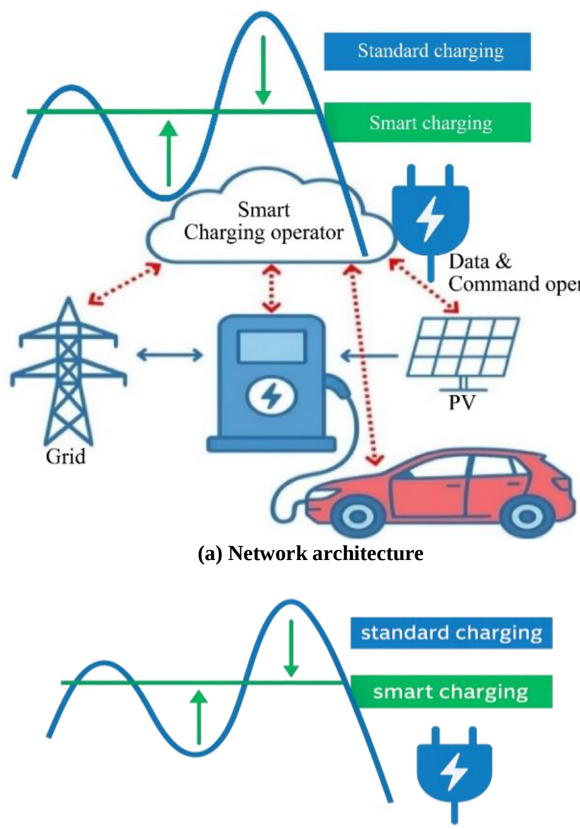
4.2.2. Isolated DC/DC Converters

Isolated converters add a level of safety to the system by protecting users from the risk of electric shock during direct coupling between the charger and the vehicle [63]. The IEC 61851-23 standard recommends isolation between the AC power grid and the EV battery [64]. The primary and secondary sides of the converter are physically separated by creating a gap between the input and output through magnetic isolation in a transformer.

A wide range of isolated converters is available, including Flyback, Forward, and ZETA converters [65-68]. These are characterized by simple designs and fewer switches. Though traditional converters often suffer from poor transformer operation, inefficient utilization of switches, hard switching, and the need for inductors and capacitors capable of handling high currents. Additionally, the stress on the switches is unevenly distributed. These limitations make traditional converters unsuitable for the isolated DC-DC stage in high-power charging applications.

The details of isolated DC/DC converters for EV charging are presented in Table 4, which gives an overview of novel topologies, highlighting the diversity in topology studied and its relevance to several specific applications. It is notable that there is a clear progression toward increasingly more powerful charging levels, as several studies target units on the order of several hundred kilowatts, and even megawatt-level charging. The authors in [69] propose a 1 MW Quad Active Bridge (QAB) converter suitable for solid-state transformer-based charging, citing its suitability for high power level with competition and minimizing current stress on diodes. Ability to charge at higher power will help mitigate the time intervals for charging, allowing for ultra-fast charging.

There is also a tendency to continue the adoption of Dual Active Bridge (DAB) topologies for applications that require power flow in both directions and integrate with energy storage systems seamlessly [70, 71]. Due to the inherent bidirectional nature of DAB, it is ideal for inclusion of capacity in Vehicle-To-Grid (V2G) functionalities and battery buffering. Additionally, [70] investigates the performance of the DAB in comparison to the Interleaved Boost Converter (IBC) in the context of high-speed DC charging, considering the balanced nature of efficiency, volume, and component count among the various topologies, and their respective trade-offs. Related reference [72] investigates an interleaved resonant switched capacitor converter for megawatt-level, highly efficient electric powertrains in heavy-duty vehicles, and demonstrates that the topology has merit with respect to specialized high-power applications. In a similar view, [73] reviews a multiphase interleaved converter providing accurate charging current, which is crucial for maintaining battery health and extend the battery life cycle. Other well-known topologies are for step-down medium voltage Neutral Point Clamped (NPC) converter [74], as well as some other modified topologies [75-77], which were established in order to boost productivity and/or decrease the number of components or improve such concerns as voltage balance or current ripple.



(a) Network architecture

(b) Smart (peak shaving) vs. standard charging

Fig. 7 Smart charging system: (a)Network architecture, and (b)Smart (peak shaving) vs. standard charging.

Table 4. Performance features of isolated DC-DC converter topologies for EV charging

Ref.	DC-DC Topology	Key Features	No. of Switching Devices	Power (kW)	Galvanic Isolation	Bidirectional
[78]	BUCK	Mitigates voltage drop in low voltage networks via reactive power compensation from a controlled bi-directional converter	1	50	☒	☑
[75]	Modified topology	Eliminates transformer, reducing cost/volume; balanced bipolar DC buses with minimal ripples	8	240	☑	☒

[73]	Multi-phase Interleaved	Precise charging current control is enabled by small inductors	6	12	☒	☑
[74]	Neutral Point Clamped	High-efficiency, compact converter using off-the-shelf SiC for stepping down rectified medium-voltage	4	50	☑	☒
[76]	High-Power Three-Level (Parallel Structure)	High power output, DC bus compatibility, and removal of the NPC converter's balancing circuit.	8	240	☒	☒
[79]	Phase-Shifted Full-Bridge	ZVS operation for efficient, cost-effective high-power conversion (loss analysis).	4	50	☑	☒
[70]	DAB and IBC	DAB and IBC comparison for fast DC charging based on efficiency, volume, and components.	DAB 8 IBC 6	350	DAB ☑ IBC ☒	☑
[71]	DAB and PPCU	Efficient multi-electric vehicle with extremely fast charging with partial power processing.	16	6*350	☑	☒
[69]	QAB	Solid-state transformer-based charging for diverse batteries using a balanced cascaded H-bridge rectifier, reducing device current stress	16	1000	☑	☑
[80]	SEPIC	Modular design with fault ride-through and redundancy for enhanced reliability	3	600	☑	☒
[77]	Multi-phase Interleaved Buck	Reduced output capacitor current ripple, current sharing, reduced filter and radiator sizes, and increased efficiency	6	576	☒	☒
[72]	Interleaved Resonant Switched Capacitor	High-efficiency megawatt-level electric powertrain for heavy-duty vehicles	12	500	☒	☒

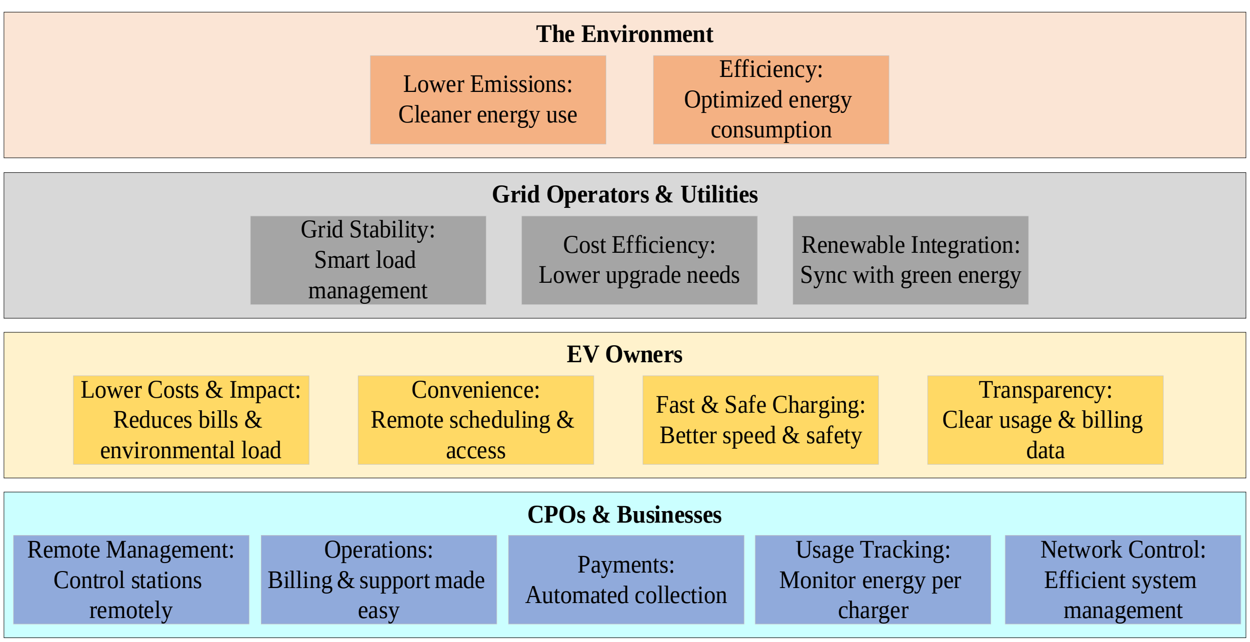


Fig. 8 Smart EV charging: Key benefits for environment, grid operators & utilities, EV owners, and CPOs & businesses

As Figure 8 illustrates, smart charging technologies have an extensive background of advantages in various industries, and the main one is the favorable impact they have on the environment. Through equalizing the consumption with the renewable availability like solar and wind energy, smart charging has a great potential in minimizing the emission of greenhouse gases and encouraging better use of energy. These technologies help grid operators and utilities to enhance grid stability (via dynamic load management), support demand-response programs, and delay the costly infrastructure upgrades by pushing charging to expensive-to-run off-peak periods.

For EV owners. For EV owners, the system delivers economic and practical advantages by minimizing electricity costs, enabling real-time monitoring, and allowing remote scheduling of charging sessions-thus enhancing convenience and operational safety. Lastly, Charge Point Operators (CPOs) and businesses benefit from increased operational efficiency via centralized remote control, automated billing, and analytics that reveal user behavior, station performance, and system optimization. These collective benefits highlight the strategic role of smart charging in advancing decarbonized transportation and intelligent energy networks. Smart charging of EVs is therefore associated with a set of functional and technical requirements in order to ensure system reliability, the efficient operation of the system, and consequently the capability of these systems to interact with the rest of the grid and their users in a dynamic manner. Table 5 collates these basic features to be considered in designing and deploying intelligent EV charging infrastructure.

Table 5. Key functional and technical requirements for smart EV charging systems

Requirement	Description
Real-Time Communication Capability	Requires continuous low latency data communication between the EV, charger and central management platform for monitoring status, receiving grid signals, and implementing adaptive control strategies.
Forecasting and Control Intelligence	The needs predictive algorithms are to estimate the energy demand and optimize the charging periods and activities in accordance with grid limits, user movement, and dynamic electricity charges.
Cybersecurity and Data Protection	Must incorporate robust security protocols (authentication, encryption, secure data storage) to protect cloud-based control and user data exchange against cyber threats and unauthorized access.
User-Centric Interfaces	Should offer accessible and configurable interfaces for users to schedule charging, monitor performance, and set preferences remotely, enhancing usability and flexibility.
Integration with DERs	Needs the capability to interface with DERs like photovoltaic systems and energy storage units to enable local energy use and grid support.
Modularity and Scalability	Infrastructure design must allow for phased deployment, functional upgrades, and future expansion without major structural changes, enabling cost-effective growth as EV adoption increases.
Interoperability and Standardization Alignment	Should be compatible among various EVs, EV Supply Equipment (EVSEs), and backend systems by meeting the various industry requirements. This is essential for successful integration, neutrality of the vendors, and long-term sustainability.

4.3. State of the Art of Smart Charging Strategies

As the EVs begin to reach deeper into the market, smart charging strategies have become necessary in order to guarantee efficient use of energy and grid stability. A hybrid charging structure was proposed in [93] that combines a centralized mechanism of scheduling with a decentralized control algorithm enablers to facilitate real-time EV charging in a situation with varying wind power supply and stochastic driving behaviour. The solution was found to converge well to optimum scheduling with its trade-off in charging demand and renewable generation. In [94], to enhance the performance of the grid and to make the grid cost-effective, a smart load scheduling strategy was proposed, which applies high-level intelligent optimization algorithms.

This method minimized the thoughts of the users, especially at slow charging stations, minimized the cost of charging, and maximized the grid stability at different load conditions. In [95], a sigma-modified proposed adaptive control method, which provides resilience to grid non-idealities and parametric uncertainties by real-time sustenance of control updates aimed at regulated charging behaviour. A special version of EMS that supports hybrid fast-charging stations was invented in [96], which includes multi-battery configurations and PV generation.

The EMS has DER constraints to develop self-sufficiency and minimise dependency on grids. Also, [97] proposed a dual-mode charging scheme, which allows also AC and DC delivery with the help of auxiliary DC source(s) like PV, batteries, or other EV. This layout enhanced the performance of charging because AC-DC conversions were not made unnecessary, and relieved the power grid.

All these efforts depict an apparent trend of decentralization, smartness, and smart charging that is renewable incorporated. These strategies facilitate grid resilience, economic feasibility, and a sustainable use of energy by matching the behavior in EV charging and the grid state of real-time and availability of renewable energy.

4.4. Enabling Standards for Smart Charging

To deliver EV charging infrastructure with the same performance, safety, and security level as conventional vehicles, it is imperative to standardize their communication protocols. The various communication protocols have been developed to improve the interoperability between EV and Electric Vehicle Supply Equipment (EVSE) [98, 99].

Among the most prominent are the Society of Automotive Engineers (SAE) protocols, such as J2931, J2836, J2847, and J1772 [100]; International Electrotechnical Commission (IEC) standards, including IEC 61850-7-420, IEC 62196, and IEC 61851 [101]; and open communication protocols, such as the Open Charge Point Protocol (OCPP), Open Inter Charge Protocol (OICP), and Open Clearing House Protocol (OCHP) [102], see Figure 9.

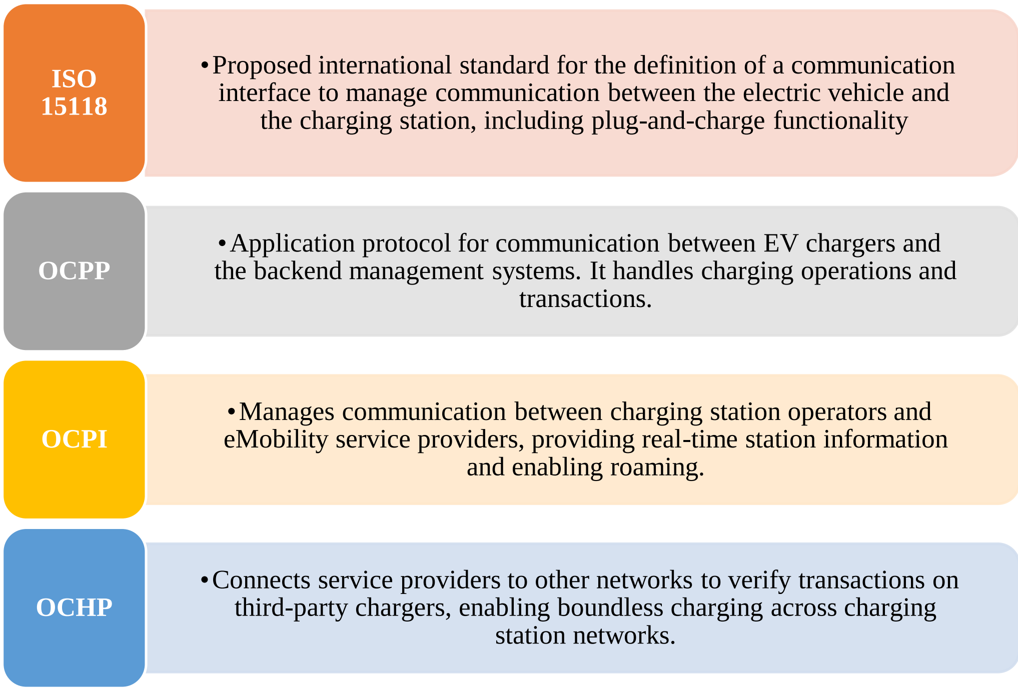


Fig. 9 Smart charging protocols for electric vehicles

4.4.1. Open Charge Point Protocol (OCPP)

The Open Charge Alliance (OCA) developed OCPP, an open-source, vendor-neutral protocol that has become the de facto standard for communication between EV Chargers and Management Systems (CSMS) [103].

This protocol simplifies interoperability, ensuring seamless integration of equipment from different manufacturers. OCPP enables key functionalities including:

- Monitoring and controlling access to individual charging stations.
- Tracking and managing charging statuses.
- Facilitating payments and reservations.
- Exchanging usage data between charging points and central systems.

4.4.2. Evolution of OCPP

OCPP has evolved significantly since its inception to meet the growing demands of the EV charging ecosystem. From basic charging management to advanced smart charging and V2G capabilities, its expanding functionality reflects the industry's move towards intelligent and sustainable solutions [104]. This evolution, from its initial focus on simple transaction management to the sophisticated features of the latest versions, is visually depicted in Figure 9, which illustrates the chronological progression of OCPP development.

For a side-by-side summary of key functionalities across versions, see Table 6: Feature Comparison of OCPP 1.6, 2.0.1, and 2.1.

Many research studies have investigated the use and improvement of OCPP in different areas of EV charging facilities. These include cost reduction strategies, integration with Electric Vehicle-to-Grid (EV to Grid) systems, improved charge management, and enhanced security.

For instance, in [103], the potential for minimizing charging station investment costs through OCPP implementation and integration is investigated, and the results show that smart charging-enabled grid services can facilitate interconnection and advanced services within the EV charging infrastructure.

Table 6. Feature comparison of OCPP 1.6, 2.0.1, and 2.1

Feature	OCPP 1.6(2015)	OCPP 2.0.1(2020)	OCPP 2.1(2025)
Smart Charging	Basic	Advanced	More Flexible
Charging Profile Management	Limited	Enhanced	Optimized
Offline Behavior	Basic Handling	More Control	Improved Mechanism
External Charging Limit	Not Available	Supported	Extended Capabilities
ISO 15118-20 Support	Not Available	Partial	Full
Bidirectional Power Transfer (V2X)	Not Supported	Introduced	Enhanced
DER Control	Not Available	Basic	Advanced
Battery Swapping	Not Available	Introduced	More Features Added

In [105] EV charging management is integrated into the vehicular to grid concept and a proposed extension of OCPP that allows users to predefine preferences in charging parameters like start time, duration, place, price, and desired power and battery charge level is introduced along with an Android-based application for reservation and payment process. In [106], systems effective for the recharging process are analyzed, and it is emphasized that the negotiation process between using stations and central stations for recharging camping should be optimized to improve the efficiency of the grid and ensure responsible communication between users and recharging stations.In [107] the focus shifts to implementing the EV domain within OCPP to enable secure data exchange between central servers and charging points, addressing privacy and security concerns by analyzing potential threats and scenarios of data exposure among various stakeholders.

5. Challenges and Recommendations

Since the EV charging process is becoming more and more common in our lives, it entails a variety of multifaceted issues, specifically when it comes to energy consumption, the robustness of systems, and the overload on electric grids. It is believed that the smart charging technologies will help to overcome these problems. However, there is no adoption of such systems without hurdles, particularly where it is done in relation to the sources of RE.

High infrastructure costs up to grid balance and interoperability concerns are just a few reasons that smart charging is not able to achieve currently, due to multiple factors.

These difficulties will be addressed only through the joint efforts of innovative technological solutions, favorable regulation policies, and effective coordination of infrastructure construction. To give a better picture, Table 7 summarizes some of the most burning issues connected to smart charging, and there are some recommendations based on control in practical terms to allow its more advanced and prevalent application.

Table 7. Summary of challenges and **recommended solutions in smart EV charging**

Challenge	Description	Recommendation
High Cost of Components and Infrastructure	Smart charging requires costly components, including power electronics, energy storage, and communication systems.	Further develop cost-effective power electronics, optimize system sizing, and provide financial incentives for users and utility providers.
Charging Reliability	Renewable energy sources are intermittent, which can disrupt the availability and consistency of Electric Vehicle (EV) charging.	Improve power electronics, control systems, and communication technologies; integrate BESS for energy buffering.
Charger Availability and Accessibility	Charging stations are unevenly distributed, especially in rural and underserved areas, limiting access to smart charging.	Apply strategic site and network planning, implement enabling government policies, and invest in public-private infrastructure development.
Charging Interoperability	Poor compatibility across Electric Vehicle (EV) types and chargers is caused by a lack of standardized connections, chargers, and communication protocols.	Develop and implement universal standards for EVs and charging systems to ensure cross-platform compatibility and seamless user experience.
Grid Impact on Stability and Power Quality	High-volume, uncoordinated charging can overload the grid, causing voltage deviations and frequency instability.	Deploy smart charging strategies, integrate DERs, and enable V2G/V2X technologies to enhance grid flexibility.

6. Conclusion

The effective switch to universal electromobility requires effective, efficient, reliable, and scalable charging infrastructures. The current review has examined recent developments in fast charging, with a particular focus on the interfaces between system architectures, international charging standards, and smart energy management. International standards play a crucial role in terms of interoperability, safety, and harmonization of the market, and future development of onboard and off-board charging (particularly, bidirectional (V2G) systems) plays an augmentative key in developing EVs as part of the contemporary energy infrastructure. Despite the prevalence of wired charging, there are some encouraging trends of diversification in both the evolution of wireless charging and battery swapping. Using architectural studies, the complementary issues of isolated and non-isolated DC/DC converters are focused on unveiling the efficiency and reliability of power electronics through the efficient utilization of these converters in a variety of applications and at a scaled level of power distribution. A mixture of renewable energy sources in charging EV has become critical, which strengthens environmental sustainability and the stability of the grid. OCPP enables the implementation of smart charging approaches that are essential to regulate the energy demand, real-time interactions, and optimization of the charger's grids. The development of OCPP 1.6 to 2.1 is a sign that the direction is taken towards more stable, secure, and smart system.

To develop DC fast charging, a decentralized perspective is needed uniting technical creativity, standardization, renewable combination, and advanced energy management. Ongoing research and development are crucial in dealing with scalability, interoperability, reliability, and environmental concerns. This review provides the overview of the existing technologies and the new trends, which can be used as a guide by the researchers, policymakers, and industry players determined to pursue sustainable electromobility and the smooth switch-over to electric transportation.

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