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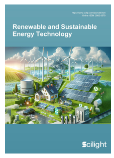

Review

Advancements in EV Charging Standards and Technologies for Sustainable Transportation

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How To Cite: Mdallal, A.; Yasin, A.; Alaboudy, A.H.K.; et al. Advancements in EV Charging Standards and Technologies for Sustainable Transportation. *Renewable and Sustainable Energy Technology* **2025**. https://doi.org/10.53941/rest.2025.100010

Received: 16 July 2025
Revised: 7 September 2025
Accepted: 22 September 2025
Published: 21 October 2025

Abstract: Electric vehicles (EVs) are a transformational and environmentally friendly means of transportation that are powered by electricity and are increasingly being acknowledged as a sustainable alternative to traditional internal combustion engine vehicles. This paper investigates the field of EV charging standards and explores the innovative charging technologies in North America, Europe, and China. It underscores the importance of established schemes in supporting smooth charging processes which accordingly facilitate the global adoption of EVs. Advanced charging technologies, including Vehicle-to-Grid (V2G) systems, wireless charging, and off-grid solutions, highlighting their potential to transform the EV ecosystem, are introduced. The on-ground deployment of these technologies is demonstrated by exploring a few real-world implementation examples. The paper also emphasizes how charging regulations and standards can boost sustainability, mitigate the concerns of limited driving ranges, and establish resilient infrastructure. The transition to electrified transport depends on the deployment of interoperable charging standards, advances in charging technologies, and coordinated business models that enable renewable-integrated and storage-enabled charging infrastructure.

Keywords: electric vehicles; charging infrastructure; EV charging standards; advanced charging technologies

1. Introduction

In recent years, the passenger vehicle sector experienced swift electrification pushed by regulatory initiatives, manufacturer commitments, and declining battery costs [1,2]. In 2024, global electric vehicle (EV) sales surpassed 17 million units as shown in Figure 1a,b, representing about 25% increase year-on-year. By the end of 2024, the global EV stock reached around 58 million vehicles, representing around 4% of the global light-vehicle fleet. Growth has been regionally uneven: China represents the largest proportion, whilst Europe and the U.S. exhibit fluctuating adoption due to varying policy and market conditions [3].

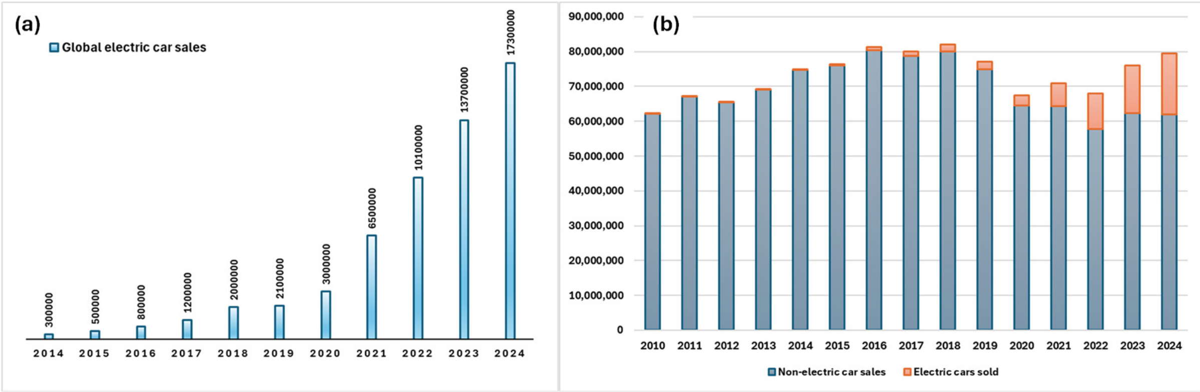

Figure 1. EV sales around the globe; Data obtained from: (**a**) International Energy Agency [3], (**b**) Our World in Data [4].

EVs reduce direct emissions of CO_2, NO_x, and particulate matter in comparison to internal combustion engine vehicles, which attracts attention from regulators and fleet operators aiming for emissions reductions and enhanced urban air quality [5,6]. The rapid rise in EV numbers generates new operational and planning requirements for power systems and urban infrastructure.

A primary barrier to the wide adoption of EVs is the availability, reliability, and scalability of charging infrastructure. Fast charging specifically presents issues for grid integration, including peak demand and local network reinforcement, and raises planning inquiries regarding station siting and capacity [7–9]. The infrastructure challenges intersect with customer expectations regarding cost, convenience, and uptime, which in turn affect EV adoption and charging behavior.

Technological developments such as fast and ultra-fast DC charging, wireless (inductive) charging, bidirectional Vehicle-to-Grid (V2G) systems, and distributed renewable-powered charging, present opportunities for overcoming barriers by decreasing charging durations, enhancing accessibility, and facilitating adaptable interactions with the power system [10–13]. The advantages of these technologies rely on standards, communication protocols, and commercial models that facilitate interoperability and grid services.

Despite significant research on specific charging technologies and national standards, there exists a lack of comparison of charging standards and communication protocols across regions. Further, a cohesive impact assessment exercise is needed to evaluate how these standards would affect the integration of rapidly evolving renewable- and storage-based charging technologies.

This paper introduces the essential charging standards and protocols, examines recent charging technologies, and explores relevant use cases. The significance of standardization, technological advancement, and renewable-integrated charging on the interoperable and sustainable deployment of EVs is well discussed within the paper sections. The paper presents an objective comparison of the deployment drivers and business models of EV charging infrastructure worldwide, offering valuable insights for technology designers, grid planners, and decision-makers.

2. EV Charging Standards and Protocols

The charging infrastructure for EVs is of considerable importance due to its central role in enabling the growth, integration with the power grid, and everyday usage of these vehicles [14,15]. A charging station typically comprises several essential components that are required for the efficient, safe, and secure charging process. These elements consist of a charging wire, charging stand, attachment plug, power outlet, and vehicle connector. The protection system is also an essential mechanism for ensuring the safety and reliability of charging equipment. The configuration of charging stations may display variances across different nations as a result of several aspects, encompassing but not limited to grid frequency, voltage, electrical grid connection, and standards. To adequately serve urban users and fit with the aesthetics of modern smart cities, chargers should provide high charging power to enable short charge times. This specific characteristic enhances the charger's capacity to efficiently transfer a substantial amount of power, while also occupying a condensed physical footprint. It is imperative that the suggested charging facility demonstrates economic efficiency, thereby mitigating the expenditure overload on the consumer side. Additionally, the used gadget demonstrates a compact and lightweight design, hence augmenting its portability and user-centric nature. In fact, the collective charger characteristics are crucial in determining its overall effectiveness and attractiveness.

Presently, there exists a worldwide endeavor to define and implement a comprehensive set of standards with the objective of guaranteeing the stability and safety of charging stations. The standardization of EVs is a multifaceted challenge as it necessitates the harmonization of two distinct technological domains, specifically automotive and electric.

2.1. Regional Standards Overview

The adoption of EVs and associated policies vary significantly among regions, resulting in various technical and regulatory challenges. China dominates new EV sales and fleet growth, implementing strong industrial and infrastructure policies that reduce costs and accelerate market expansion. Europe exhibits robust, yet varied, adoption rates, with market shares differing by country; Norway and other Nordic countries stand out with nearly complete electrification of new car sales. In contrast, U.S. deployment is influenced by federal funding regulations and state initiatives that link infrastructure development to particular procurement and interoperability standards. The differences present practical obstacles to harmonization: fragmented protocol adoption, divergent incentive structures, and differing timelines for mandatory features suggest that a universal standardization approach is difficult without focused international collaboration [16–18].

The United States adheres to the SAE J1772 standard that details the specifications of EV charging systems [19]. It addresses the most important physical, electrical, and performance criteria for North American EV charging infrastructure. The classification of EV charging systems includes three basic classes, based on their rated power, voltage, and current specifications [20]. The three categories are known as AC Mode 1, AC Mode 2, and DC Mode 3. In AC Mode 1, the EV charger is integrated within the vehicle itself, compatible with two AC voltage levels, particularly 120 and/or 240 V. The peak current output is 15 A and the peak power output of 3.3 kW. The AC Mode 2 is quite similar to AC Mode 1 with higher current and power ratings. It has been also embedded into the vehicle and designed to work on AC voltage of 240 V. The peak output current and power are respectively 60 A and 14.4 kW. Rather, the third class of chargers is based on DC power injection, including an external charger kit, directly supplying DC power to the EV battery. The third class (known as DC charging modes) is based on the SAE standards and includes two sub-modes, DC mode 1 and DC mode 2. The differences between these two modes are specified in Table 1 [21].

Table 1. SAE EV charging modes [22,23].

Charging Mode	Equipment and Supply	Charging Specs	Estimated Charge Time
AC Mode 1	On-board charger; Single-phase from household outlet	120 V at 12 A (1.44 kW); 120 V at 16 A (1.92 kW)	17 h (20–100%)
AC Mode 2	On-board charger; 208–240 V AC Single-phase	Up to 19.2 kW (Typ. 7.2 kW); Up to 80 A (Typ. 30 A)	3.5–7 h
DC Mode 1	Charging station output voltage: 50–1000 V DC	Up to 80 kW (Typ. 50 kW); Up to 80 A (Typ. 50 A)	20 min (20–80%)
DC Mode 2	Charging station output voltage: 50–1000 V DC	Up to 400 kW (Typ. 50 kW); Up to 400 A (Typ. 50 A)	<10 min (20–80%)

In line with existing battery-powered systems, EVs necessitate a means of replenishing their batteries subsequent to their utilization. In accordance with the established charging protocols outlined in IEC 61851, various charging modes can be identified [24]. These charging modes are presented in Table 2 [24,25]. Figure 2 illustrates the connection schemes of the main three charging modes infrastructure. Despite the early emerge of EVs back in the 19th century [26], the recent substantial resurgence of EVs is primarily attributed to growing concerns surrounding greenhouse gas emissions and the excessive reliance on fossil fuels. In the early generations of EV charging infrastructure, the available solutions were relatively rudimentary. These initial charging options basically consisted of slow chargers (Mode 1), which relied on conventional household outlets for power supply. The limitations of these methods were primarily observed in terms of charging speed and infrastructure scalability. Mode 1 charging, as observed, typically necessitates an overnight charging duration for EVs, thereby rendering it impractical and inconvenient for widespread acceptance. The classification of charging modes is typically determined based on the charging duration, which is influenced by factors such as the power rating and current of the charging station. The normal charging mode, commonly employed in Europe, is typically characterized by a power rating of 3.3–3.7 kW. The key observation of this power rating's utilization can be found in various charging systems across the region. The following specifications correspond to a 230 V socket outlet designed for use with a single-phase AC charger that has a current requirement of 16 A. This mode of charging station infrastructure has been identified as a favorable choice for deployment based on its cost-effectiveness and user-friendly features in both residential and commercial settings. Hence, the installation of such power stations is presently required by national regulations in most countries. Despite its convenience for residential purposes, a significant limitation of this technology is its rather sluggish charging rate, which generally yields a more 2-5 miles of driving range per hour of charging.

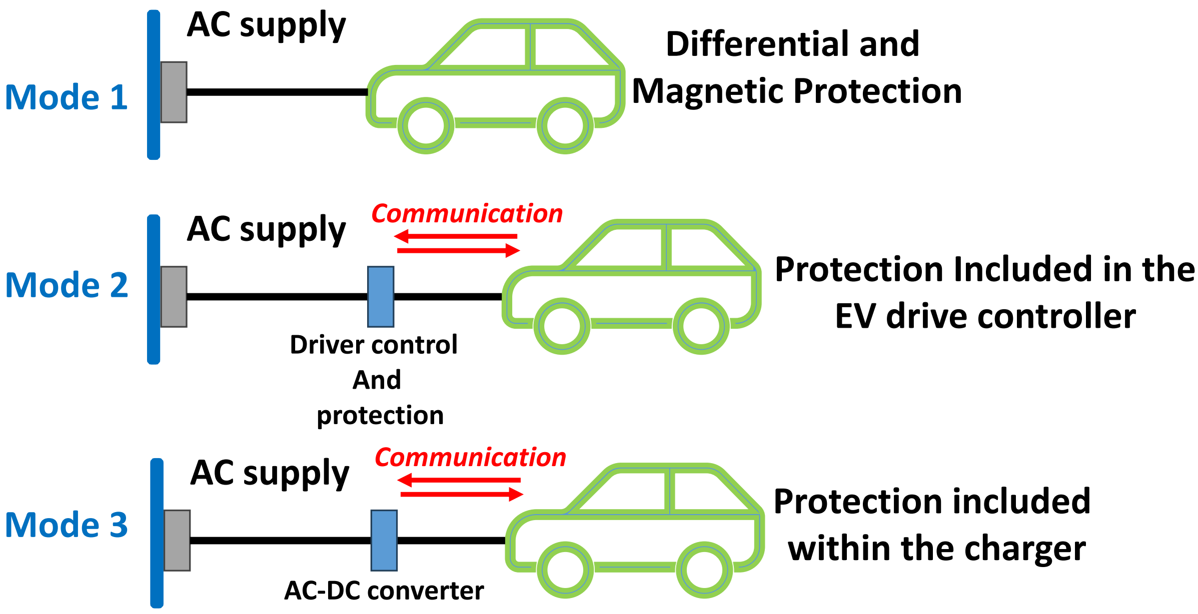

Figure 2. Different EV Modes characteristics (Adapted from [27], Open Access).

In contrast, the semi-fast charging mode (Mode 2) is characterized by higher power ratings ranging from 7 to 22 kW. This mode can be achieved by utilizing either a single-phase, 32 A power outlet or a three-phase 16 A outlet, typically delivering 10 to 60 miles of range per hour of charging. The infrastructure mode is characterized by its direct connection to the AC supply network, facilitated by a controlled pilot contactor that decouples. This is the user and the equipment involved in the system. Moreover, the main advantage of Mode 2 charging infrastructure is that the station can adjust its charging rates based on the grid demand during peak times. Finally, the third mode of charging infrastructure (known as DC fast charging-Mode 3) is considered the fastest charging system utilizing DC provided by an off-board charger. However, despite its fast-charging advantage, this mode requires a very heavy and complex infrastructure depending on its category/type, i.e., fast or super-fast chargers.

The standard DC fast charger signifies the beginning venture towards expedited EV charging. These chargers are commonly utilized in the power output range of 50 kW to 90 kW and have the capability to deliver an estimated range of 60–80 miles during a 20-min timeframe. The super-fast charger has been developed specifically to meet the changing needs of the latest generation of EVs, which are equipped with larger battery capacity and higher charging thresholds. This charger represents a significant advance in charging capabilities. The chargers operate within a higher power output range, spanning from 90 kW to 150 kW. Such chargers are capable of providing a range of roughly 120–180 miles within a 20-min period.

Table 2. Charging infrastructure comparison [19,20,27].

Type	kVA	Charging Time	Charging Method	Recommended Location	Cost per Unit
Slow Recharge (Mode 1)	1−5	6 to 8 h for 100% 3 to 4 h for 80%	AC: 1 phase, 230 V, 16/32 A	Private locations Such as parking on public streets and a fleet of company cars	Less than $5000
Semi-fast Recharge (Mode 2)	10–25	1 h for 100% 30 min for 80%	AC: 3 phase, 230V, 32/63A	Car rental company and service stations	$5000 to $6500
DC Fast charging (Mode 3)	180−400	5–25 min	According to charger	Service stations	$6500 to $65,000

To further clarify, slow (Mode 1) chargers generally function at 1–5 kVA (charging overnight), semi-fast (Mode 2) at 10–25 kVA (hours), and DC fast chargers vary from 50 kW to 150 kW, providing 20–80% state of charge in few minutes, a spectrum that suggests very different siting, grid capacity, and cost requirements. The capital cost per unit exhibits significant variation (less than $5000 for slow chargers compared to $6500–$65,000 for DC fast chargers), affecting deployment strategy and the decision between many low-cost slow chargers or a few numbers of high-cost fast charging locations.

The GB (Guo Biao) EV standard represents a proprietary charging infrastructure exclusive to the People's Republic of China, distinguishing it from international charging protocols prevalent in other global jurisdictions. Enshrined as an imperative regulatory framework, this standard operates in congruence with China's technical regulations, reinforced by statutory instruments. It has been instituted under stringent legislative oversight and prescriptive directives with the objective to safeguard public health, ensure the integrity of private assets, and bolster overall safety. Any standards diverging from these stringent criteria are categorized under the advisory or quasi-mandatory bracket. The demarcation between Mandatory and Recommended GB standards is discerned through a specific prefix code system, which serves as an identifier for their regulatory standing [23,28].

2.2. Charging Protocols

2.2.1. SAE J1772 Charging Protocol

The California Air Resources Board (CARB) is the principal contributor to establishing the SAE J1772 standard. The Magne Charge (SAE J1773) system, relied on inductive technology, was incorporated into the early EV productions such as General Motors EV1 and Toyota RAV4 EV [29,30]. However, the ecosystem witnessed substantial transformations with the adoption of SAE J1772-2009, a generally accepted standard by prominent EV manufacturers such as Chevrolet and Nissan [31]. The J1772 connection, as shown in Table 3, was meticulously designed to exhibit a notable degree of robustness, allowing it to endure prolonged utilization and exposure to diverse environmental factors. Furthermore, the device was intentionally engineered to accommodate single-phase alternating current (AC) electrical networks, prevalent in regions such as North America and Japan. Furthermore, the device was calibrated to operate optimally within the voltage ranges of 120 V or 240 V.

Table 3. SAE J1772 hardware description [32].

Feature of Connector	Specific Description
Diameter	Measures at 43 mm (equivalent to 1.7 inches)
Number of Pins	Total of 5 pins
Durability	Engineered to last 10,000 mating cycles, translating to an impressive lifespan of over 27 years with daily use.
Supported Modes	AC Mode 1, AC Mode 2, DC Mode 1, DC Mode 2 (An AC Mode 3 was planned but never executed)

Insights into the global utilization of the J1772 connection reveal varied adaptation trends across different geographical regions. In the U.S., the J1772 connection became a norm, largely due to a widespread charging ecosystem, which was bolstered by initiatives such as ChargePoint America. This smooth integration symbolizes the streamlined implementation of EVs in the United States. Conversely, Europe presented a more nuanced picture. The region initially leaned towards adopting the SAE J1772-2009. However, as the EV charging infrastructure evolved, Europe progressively transitioned to the IEC Type 2 "Mennekes" connector. This changeover process in Europe underscores the intricate and evolving nature of the EV charging infrastructure across different regions [33].

As shown in Table 4, Control Pilot is key for facilitating communication. The intricate design of the system secures a continuous synchronization between the vehicle and the charging apparatus, hence optimizing the efficiency of the charging procedure.

Table 4. SAE J1772 communication [34].

Role/Function	Elaborate Explanation
Communication Medium	Serves as the bridge between the EV and the EVSE, ensuring seamless interactions.
Nature of Signal	Employs a square signal of 1 kHz frequency, oscillating at ±12 V, crucial for identifying EV connectivity, kickstarting the charging process, and data relay.

2.2.2. GB/T Charging Protocol

The GB/T charging protocol epitomizes China's forward-thinking approach in the EV sector. Amid the burgeoning expansion of EVs, China embarked on a journey to sculpt a national standard, finely attuned to its distinct technological framework and infrastructural parameters. The outcome was the GB/T charging protocol: a comprehensive solution that elegantly bridges both AC and DC charging mechanisms, instead of merely acting as a connector. This multifaceted capability provides an adaptive charging environment, fitting diverse urban and remote contexts [21].

Table 5 sheds light on the intricacies and comprehensive nature of the GB/T charging protocol. Every facet, from its fundamental design elements to its vast charging functionalities, highlights China's strategic preparation in championing a progressive charging infrastructure.

Table 5. GB/T hardware description [35].

Protocol Attributes	Detailed Insight
Charging Mechanisms	Inclusively caters to AC and DC charging paradigms
Design Philosophy	Crafted with an understanding of China's specific infrastructure dynamics, emphasizing user-friendly interfaces and durability
Pin Arrangement	A differentiated pin design for AC and DC configurations, meticulously devised to guarantee safety and effective power transition
Charging Variability	Provides an array of power and voltage thresholds to cater to varied EV charging requirements

Table 6 highlights the regional adoption of the GB/T protocol. Though its mainstay is within China, its standardized design principles and the emergence of compatible adapters enable international vehicles to effortlessly integrate with China's expansive charging matrix.

Table 6. GB/T Global perspective.

Region	Utilization Trends
China	Predominantly adopted, aligning with national strategies and overarching infrastructure design
Global Perspective	Limited adoption outside China due to regional standard deviations, but the presence of adapters ensures interoperability

The GB/T protocol encompasses intricate communication strategies, essential for the optimal function between EVs and their associated charging apparatus. Primary communication facilitates the interaction between the EV and the charging setup, ensuring energy transfer is optimized to the vehicle's specific needs. This primary interface ensures that vehicles are charged efficiently and in accordance with their specifications. Additionally, the GB/T protocol incorporates specific signaling dynamics. This is characterized by the employment of proprietary signaling methodologies inherent to the GB/T standard. Such methodologies are paramount in maintaining a regulated charging pace and implementing essential safety protocols during the charging process. The smart comprehensive design ensures that the energy exchange between the vehicle and the charging apparatus is both efficient and conforms to necessary safety standards.

Emerging from rigorous research and foresighted design principles, the GB/T charging protocol exemplifies China's advancements in the EV charging sector. Its design subtleties, broad capabilities, and anticipatory methodology not only set it as a benchmark for charging standards but also highlight China's progressive stance in the global EV narrative.

2.2.3. CHAdeMO

The CHAdeMO protocol emerged from a vision to establish an industry-leading rapid-charging standard for battery electric vehicles (BEVs), The CHAdeMO Association, established in 2010, emerged as a result of a cooperative endeavor among the Tokyo Electric Power Company and other esteemed Japanese manufacturers. This association symbolized the aspirations of Japan's automotive industry in the worldwide EV revolution. Table 7 provides the charging capabilities of the CHAdeMO.

Table 7. charging capabilities of the CHAdeMO.

Specification	Voltage (V)	Current (A)	Power (kW)	Achievable Range (30 min)
Initial design	500	125	62.5	120 km
Second generation	1000	400	400	-
Projected	1500	600	900	-

The principle behind the CHAdeMO protocol is grounded in the realm of DC fast charging. Unlike conventional AC chargers, which typically rely on an EV's onboard rectifier to convert AC from the mains to DC for the battery, the CHAdeMO system facilitates direct DC transfer. This direct provision of DC power into the vehicle's battery is a quintessential feature of rapid charging—dramatically reducing charging times while ensuring the battery's longevity and health. This is achieved via an intricate communication system between the EV and the charging infrastructure, ensuring precise power modulation tailored to the battery's needs. The role of the CHAdeMO in shaping the narrative of EV charging can't be understated. Its inception marked a significant shift in how the automotive industry perceived EV charging as a move from prolonged hours of charging to a more "refueling-like" experience. The Significant CHAdeMO [36].

Milestones are presented in Table 8. However, as the EV landscape continues to evolve, emerging standards show up as competitors to CHAdeMO; one notable contender is the Combined Charging System (CCS) protocol. Endorsed by a sizable section of the automotive industry, CCS claims the spotlight with its dual AC and DC charging capability [37].

Table 8. Timeline of the CHAdeMO protocol [21].

Year	Milestone
2010	Inception of the CHAdeMO association by leading Japanese entities
2018	Formative collaboration with China Electricity Council (CEC) initiated
2020	Charging capacities of 350–400 kW achieved. Preliminary ChaoJi tests carried out
2021	Unveiling of the full specifications for ChaoJi 2 (CHAdeMO 3.0).
2022	Scheduled release of ChaoJi 2 (CHAdeMO 3.0.1).
2023	Planned ChaoJi 2 field tests in Japan and the debut of Ultra-ChaoJi (CHAdeMO 4.0)

2.2.4. CCS (Combined Charging System)

Combined Charging System (CCS) collaboratively emerged by stakeholders of the US and European EV sector, including Audi, BMW, Ford, and Volkswagen. Unlike J1772-2009 Combo, the CCS heralds a new era in charging versatility. CCS caters to both AC and DC charging requirements via a singular port interface. This removes the need for a supplementary socket specifically for AC charging, which is a necessity in CHAdeMO-equipped vehicles.

As delineated in Table 9, the CCS introduces two primary connector variants: Combo Type 1 and Type 2. This bifurcation emerges from the imperative to tailor connectors to region-specific electrical standards and vehicular design predilections. The unified communication framework of the CCS, although manifesting differently based on requirements, stands as its cornerstone. This communication can broadly be classified into Basic Signaling and High-Level Communication (HLC).

Table 9. CCS connector types.

Connector Type	Basis of Development	Standards Reference	Region of Use
Combo Type 1	AC Type 1 Connector	SAE J1772/UNE EN 62196-2	USA
Combo Type 2	Type 2 Connector	UNE EN 62196-2	Europe

As showcased in Table 10, the diversity in communication is hinged on the intricacy of information exchange. While Basic Signaling ensures foundational safety and readiness checks, the HLC delves into the realm of intricate data transmissions, underpinning advanced functions like DC charging and plug-and-charge operations. This holistic approach ensures not only the efficacy of the charging process but also its overarching safety and adaptability.

Basic PWM control (IEC 61851) provides simple safety and charge enablement, whereas high-level protocols (DIN SPEC 70121/ISO/IEC 15118) enable plug-and-charge, authentication and power-management features, a functional gap that affects interoperability and smart-grid services.

Table 10. CCS communication principle.

Communication Type	Technological Approach	Transmission Medium	Standard References	Primary Functionality
Basic Signaling	Pulse-width modulation (PWM)	Control pilot (CP) contact	IEC 61851-1	Safety readiness checks, indicating connection status, and AC charging via PWM signal.
High-Level Communication (HLC)	High-frequency signal modulation	Control pilot (CP) contact (PLC)	DIN SPEC 70121, ISO/IEC 15118-series	Complex data transmission for DC charging, plug-and-charge, and load balancing.

2.2.5. Tesla Chargers

The EV domain is highly inspired by the distinct paradigm introduced by Tesla, characterized by its own elegant and smart charging architectures. Pioneering the state-of-the-art, Tesla has unfurled its proprietary EV charging stations—predominantly known as Tesla Supercharger or the emerging Tesla Mega charger. These charging edifices have come with a versatile capability, spanning three distinctive charging intensities.

Table 11 provides a holistic view of Tesla's charging speeds and their respective driving ranges. Tesla's products, though consistent with in-house core vision, adapt to the regional requirements.

Table 11. Tesla charger specifications [38].

Charging Intensity	Power Output	Specifications	Estimated Driving Range per Hour
Standard	2.4 kW	120 V (15–20 A)	3 km
Medium	19.2 kW	240 V (80 A)	Mid-range, specifics vary
Fast	144 kW	480 V (300 A)	Up to 273 km

Table 12 showcases the regional variations of Tesla's EV inlets. In essence, Tesla's approach underscores the company's ambition to not only cater to the high level global EV market but also to regional intricacies. Their seamless blend of innovation and adaptability stands out, making Tesla a flagship leader in the global EV charging arena.

Table 12. regional variations of Tesla's EV inlets [39].

Region	Tesla EV Inlet Version
US, Canada, Mexico, Japan, Taiwan	Proprietary Tesla Inlet
Europe	Type 2 or CCS Combo 2 Inlet
China	Dual AC GB/T & DC GB/T Inlets

2.2.6. IEC Type 2 Protocol

Europe's EV charging landscape has been transformed by the adoption of the IEC Type 2 Protocol. As a segment of the broader IEC 62196 international standard, this protocol stands out as a harmonized solution designed to meet the diversified charging needs of the European EV market. In 2013, the European Commission took a definitive step by making the IEC Type 2 the cornerstone of charging within the European Union boundaries [20]. While the echoes of this decision have resonated in territories like Australia and New Zealand, China has crafted its trajectory with the GB/T 20234-2 standard, which reflects also similarities to IEC Type 2. Worth mentioning, IEC Type 2 protocol traits a charging orientation that is predominantly AC-focused with capabilities of three-phase integration. Its design frame is tailored for European power dynamics, prioritizing efficient energy exchange and security. In terms of physical pin composition, the IEC Type 2 protocol offers a seven-pin configuration suitable for both single and three-phase connections, facilitating dynamic power flow [39]. These characteristics demonstrate the protocol's adaptability to European power systems and varied EV charging demands.

The IEC Type 2 protocol also has impressive power delivering capabilities as defined in the IEC 62196-2 standard. For a single-phase AC source configuration (230 V and 30 A), it gives up to 7.4 kW. For a three-phase AC setup (400 V and 65 A), the power output can go up to 43 kW. In terms of geographical dispersion, Europe remains the prime domain of the IEC Type 2 protocol, dominating the EV charging space [40,41]. However, on a global scale, the IEC Type 2 is gaining traction due to its versatility and safety traits. The IEC Type 2 charging protocol symbolizes Europe's proactive stance in harmonizing the EV charging domain.

3. Advanced Charging Technologies

Standards define device compatibility, although recent technical advancements transform charging delivery from high-power DC stations to wireless and bidirectional interfaces, significantly affecting grid integration and user experience. This section explores a few new trends in charging technologies, including Vehicle-to-Grid (V2G), Wireless Charging, and Off-Grid Charging Solutions, which include renewable energy systems and Battery Swapping Technologies. Table 13 gives an overview for EV charging methods, highlighting the key pros and cons of each one.

Table 13. Methods of charging and their comparison.

Charging Method	Description	Advantages	Disadvantages
Mode 1	Standard household sockets without any control	Simplicity and low-cost installation	Slow charging speed; limited safety
Mode 2	Standard socket with added protection and control	Moderate cost with added safety features	Still relatively slow; limited control
Mode 3	Dedicated charging station with safety features	Faster charging; improved safety	Requires dedicated infrastructure
Wireless Charging	Charging through electromagnetic fields	Convenient; no physical connection	Less efficient; slower than wired
Renewable Energy-Powered	Charging stations powered by renewable sources	Environmentally friendly; sustainable	Availability may be limited
Battery Swapping	Replacing depleted battery with a fully charged one	Quick refueling; no charging time	Infrastructure costs; limited support
V2G	Allows EVs to discharge energy back into the grid	Potential to earn money; grid support	Requires compatible infrastructure

3.1. V2G (Vehicle-to-Grid)

Vehicle-to-Grid (V2G) technology facilitates the bidirectional electrical power exchange between an EV and the electric grid [42–44]. This ability empowers EVs to not only consume electricity from the grid but also inject surplus energy back to the grid [45]. This approach has the potential to convert EVs from just passive consumers of energy to active contributors within the energy system. In other words, V2G technology facilitates the use of EVs as mobile energy storage units, feeding power to the grid when the vehicles are parked [46]. Hence, V2G brings favorable merits to the power utilities, such as better load distribution, demand reduction during peak periods, and enhancement of the grid stability [47]. During periods of high demand, (known as peak hours), EVs have the ability to discharge their stored energy, therefore reducing the load stress on the electrical grid. This discharge of energy from EVs may decrease the reliance on fossil fuel powered plants.

Moreover, V2G technology has advantages for EV owners, including the possibility of making income via the trading of surplus energy to the power grid or engagement in demand response initiatives [48]. These schemes provide incentives for EV owners to charge their vehicles during periods of low power demand, when prices are lower, and to discharge energy during times of high demand, therefore optimizing cost savings. However, the deployment of V2G has some obstacles. A powerful communication infrastructure and payment platform is necessary to provide smooth coordination among EVs, charging stations, and the electrical grid [49]. Furthermore, it is essential to exercise caution in the management of EV battery cycling for grid services in order to mitigate potential battery damage [50].

3.2. Wireless Charging

The development of wireless charging technology has presented a simple and effective means of charging EVs, eliminating the need for physical cables and connections. Inductive Power Transfer (IPT) is the fundamental mechanism of wireless charging, where electrical energy is transferred between two coils, one either in the ground or on a charging station and the other inside the EV itself [51,52]. Wireless charging devices often function by using resonant magnetic fields, so enabling the effective transmission of energy over very small distances [53]. When an EV that is equipped with a receiving coil is positioned above a wireless charging pad or station, the coils exhibit resonance at the same frequency, facilitating the transfer of energy from the pad to the battery of the vehicle [54]. This procedure eliminates the need for manual cable linkage, hence enhancing the convenience and user-friendliness of the charging process as can be observed in Figure 3.

Wireless charging has attracted considerable interest due to its possible uses in many contexts, such as public charging stations, residential charging units, and even dynamic charging systems used on highways. dynamic electric vehicle charging (DEVC), presents the potential to continually charge EVs while they are in motion on highways and streets [55]. This technology has the potential to greatly enhance the range of EVs and reduce the need for large battery packs [56,57]. Despite the potential benefits it offers, wireless charging technology encounters some obstacles. The key focus in wireless charging is on efficiency, given that energy dissipation during this process tends to be greater in comparison to conventional plug-in charging methods [58]. Furthermore, it is essential to provide a standardized framework for wireless charging systems in order to ensure connectivity across various EV models and charging infrastructure [59].

This charging method exhibits some significant benefits within its operating framework. This system is defined by its streamlined nature, high level of security, and user-friendly interface. These qualities contribute to its minimum maintenance expenses, which may be largely attributed to the absence of mechanical components. Moreover, the adoption of galvanic isolation between the EV and the power supply greatly reduces the risks associated with cable-based charging systems. This includes the use of degraded cables under unfavorable weather conditions. Another advantage is the potential for underground installation of the charging transmitter. This not only protects it from unfavorable environmental conditions, but also significantly extends the lifespan of the charging infrastructure. Additionally, it reduces the vulnerability to acts of vandalism, such as theft of charging cables and removal of crucial components, as well as other possible threats [60].

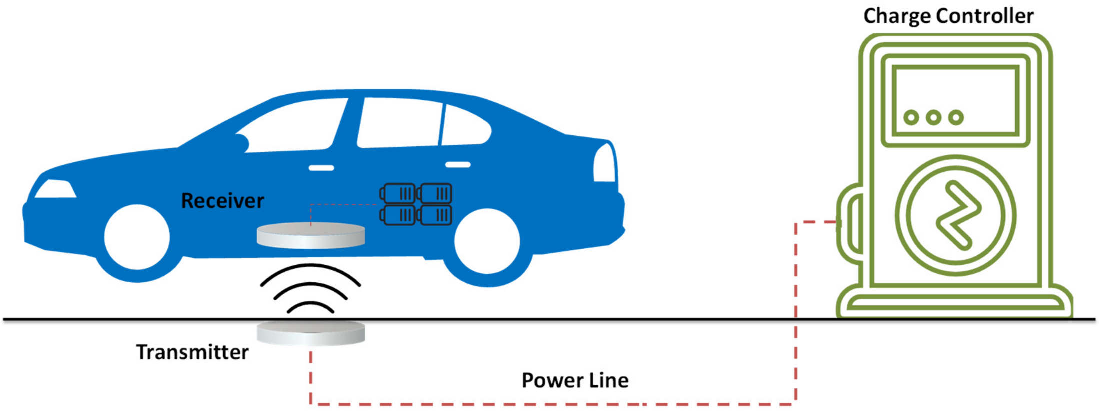

Figure 3. Simplified Schematic of Wireless Charging.

3.3. Energy Storage and Renewable-Integrated Charging

The rapid growth of EVs has generated an urgent need for reliable charging options in regions without stable grid access. Two key off-grid methods are solar-powered stations and wind-energy charging, which can function independently or together alongside battery-swapping technology that reduce downtime. However, renewable energy generation is naturally variable. Thus, off-grid chargers utilizing PV or wind energy must either use power immediately or store it to prevent energy wastage. The storage and backup needs substantially raise system costs and complexity; even advanced PV-wind-hydrogen charging systems underscore the necessity for progress in hydrogen storage to mitigate expenses [61,62].

3.3.1. Solar-Powered Stations

Solar-powered charging stations convert sunlight into electricity via photovoltaic panels, storing excess energy in on-site batteries to ensure availability even when solar irradiance is low [63]. Employing a renewable resource, these installations reduce carbon emissions related to EV charging and decrease long-term operational expenses, as solar arrays require less maintenance and can operate for years [64]. Their off-grid functionality makes them particularly advantageous in rural or distant areas where the extension of conventional transmission lines would be too costly [65,66]. Surplus energy can be stored for future use or, if grid connectivity is available, returned to the utility, so improving overall system sustainability. However, solar-powered charging stations have certain drawbacks as well. The energy production of renewable sources is subject to fluctuations due to weather patterns and geographical factors, resulting in intermittent availability of charging facilities [63].

3.3.2. Wind Energy Charging Stations

Wind turbines located near to charging stations provide an additional clean energy source, enhancing the renewable energy portfolio and increasing supply reliability during periods of low solar output [67]. The integration of wind and solar technologies reduces the intermittency associated with each resource, hence assuring more reliable power delivery. Utilizing locally generated wind power can protect station operators from variations in grid electricity prices over time [68,69]. Due to the daily and seasonal fluctuations in wind speeds, these systems depend on energy storage or backup generation to ensure uninterrupted operation, and necessitate regular maintenance of blades, gearboxes, and electrical components to preserve performance [63].

3.3.3. Battery Swapping

Battery-swapping stations mitigate fast-charging constraints by automating the replacement of depleted battery packs with fully charged ones [70,71]. The process requires only minutes, comparable to a traditional refueling stop, making it appealing to commercial fleets and long-distance trips when reducing downtime is essential [72]. Moreover, by integrating newer battery modules, operators can enhance battery health management, thereby prolonging vehicle service life without necessitating the replacement of the entire EV [70]. The implementation of battery swapping, however, depends on the standardization of battery designs across manufacturers and the establishment of a network of stations, both of which require significant capital investment. Moreover, the environmental impact of manufacturing, recycling, and disposing of interchangeable battery packs must be evaluated to ensure that this rapid solution remains sustainable [73].

4. Implementation Examples

Several representative deployments reported in the industry and literature illustrate practical trade-offs in power level, storage/back-up, site purpose and cost. These examples are provided to extract transferable lessons for standards, grid planning and renewable integration rather than to function as formal methodological case studies.

Zap Map classifies EV charging in the United Kingdom into three speed categories: slow chargers (≤3 kW, typically used overnight at residences with charging times of ~6–8 h), fast chargers (7–22 kW, typically requiring ~3–4 h for a full charge on many models) and rapid chargers (≈43–50 kW, capable of delivering ~80% state-of-charge in ≈30 min). National- and network-scale deployments show the range of system designs that follow from these classes: Norway's large fast-charging station, for example, accommodates 28 vehicles in a 30-min window via a mix of 20 Tesla Superchargers, four 50 kW DC fast chargers and four 22 kW AC points, while major Dutch highway stations provide ~50 kW fast charging and deploy sheltered stalls with integrated solar panels to serve multiple vehicle brands. Corridor- and OEM-led initiatives anticipate even higher power: several OEMs committed to piloting pan-European 350 kW chargers, with an initial rollout of 400 sites (first phase beginning in 2017) to support very-high-power recharging [74].

Tesla's V3 Supercharging [75] demonstrates a high-power, centralized fast-charging approach: sites use large-power cabinets with per-vehicle peak rates up to hundreds of kilowatts, combined with operator software to manage thermal and queuing effects. Therefore, ultra-high-power sites can improve throughput and user convenience but require substantial grid capacity, coordinated utility upgrades and advanced control/aggregation strategies to avoid local network stress.

Electrify America's rural solar L2 pilot [76,77] illustrates a distributed, low-power model that pairs sun-tracking PV arrays with local battery storage to serve off-grid sites with two simultaneous L2 points. While this approach expands access in remote locations and reduces grid dependence, its low per-vehicle power leads to long dwell times and a higher levelized cost per kWh compared with grid-connected fast charging, making it appropriate for access-focused rather than throughput focused locations.

The Sanya Skypump wind-hybrid public charging demonstration [78] shows how small-scale wind turbines integrated with storage can support municipal charging points in constrained urban settings. Such micro wind + storage prototypes can supplement local renewables but provide limited energy and therefore are best positioned for opportunistic, low-power charging or as part of a hybrid energy mix with grid connection or backup generation for reliability.

Hybrid off-grid systems reported by Karmaker et al. [69] and Fathabadi [79] (PV + biogas/fuel-cell backup and batteries) achieve greater autonomy and reliability than PV-only designs by providing dispatchable generation during low-resource periods. These hybrids reduce intermittency and can improve lifecycle emissions, yet their higher capital costs, operational complexity and maintenance requirements constrain scalability and favor deployment where grid extension is infeasible or where reliability premiums justify the investment.

Mechanical and high-power short-duration storage solutions (e.g., flywheels) examined by Erdemir & Dincer [80] are shown (Figure 4) to suit pulsed, very-high-power demands such as electric-bus fast-charging. Mechanical storage offers rapid response and high power density but introduces unique infrastructure and operational constraints distinct from electrochemical storage and therefore is most applicable to specialized fleet or depot use-cases rather than general public stations.

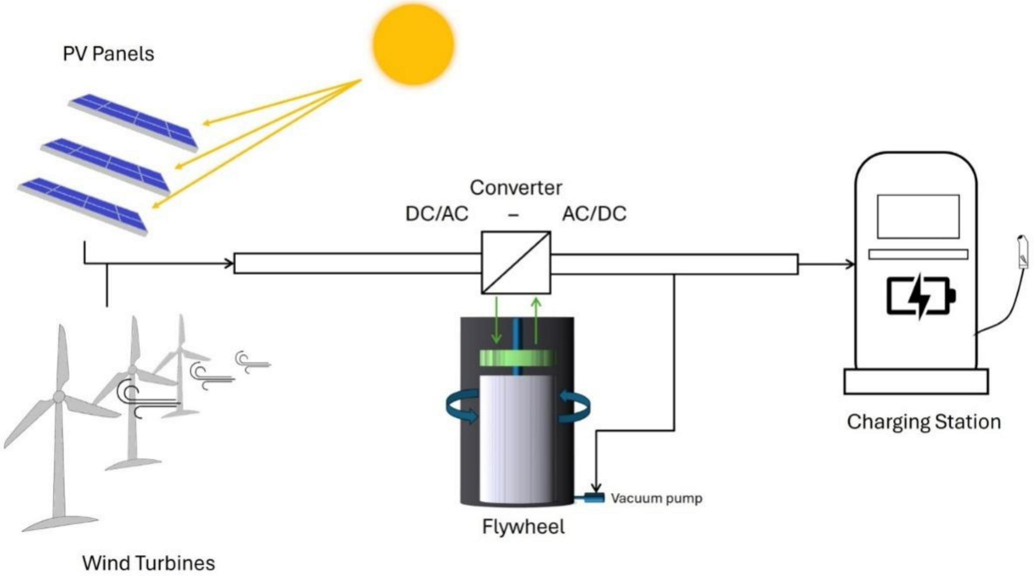

Figure 4. An illustration of the solar and wind power integrated fast charging station with a flywheel.

Across these examples the recurring trade-offs are consistent; higher per-vehicle power improves convenience but raises capital and grid requirements; renewable-driven off-grid solutions reduce grid reliance but require storage or backup that increases cost and complexity; and storage type selection (batteries, mechanical devices, fuel cells) should match the temporal and power-density requirements of the intended application. These implementation examples therefore inform how standards, communication protocols and business models must align with technology choice and deployment context.

5. Future Storage Solutions

Energy storage solutions have considerable potential in multiple aspects of integrating renewable energy generation into the grid, including distributed generation, microgrid systems, transmission and distribution networks and smart grid technologies. However, it is important to tackle the main barriers associated with energy storage in order to facilitate its widespread implementation. Additional research is essential to investigate and improve the potential, durability, cost-efficiency, and security of energy storage devices, especially electrochemical energy storage systems. Continuous technical improvements are necessary in response to the growing need for physical energy storage solutions that are both efficient and cost-effective. Future investigations should highlight the path of integrating energy storage models with operational optimization as a major area of research. A significant barrier to the incorporation of energy storage in renewable energy systems is the supplementary financial burden it places on the entirety of the system. Extensive research into innovative materials suited for the manufacture of energy storage technologies is needed in order to achieve a reduction in their cost. Furthermore, the lack of supportive regulations restricts the progress of technological advancement and leads to higher expenses, underscoring the need for policy actions that encourage the expansion of this essential technology [81].

The integration of Compressed Air Energy Storage (CAES) systems [82] into future EV charging stations as shown in Figure 5 is an effective way to tackle the escalating need for environmentally friendly EVs. The CAES technology provides effective energy storage, rapid response times, and the ability to stabilize the grid, making it a suitable addition to the developing EV ecosystem. By effectively using excess energy derived from sustainable sources and deploying it when needed, CAES has the potential to improve the reliability and availability of EV charging infrastructure, while simultaneously reducing the strain on the electrical grid during periods of high demand. however, it is important to thoroughly evaluate many obstacles, including infrastructural requirements, energy dissipation during compression and expansion processes, and the potential impact on the environment. Despite these obstacles, CAES has considerable promise in enhancing the performance and sustainability of EV charging stations, hence fostering a cleaner and more attainable future for EVs.

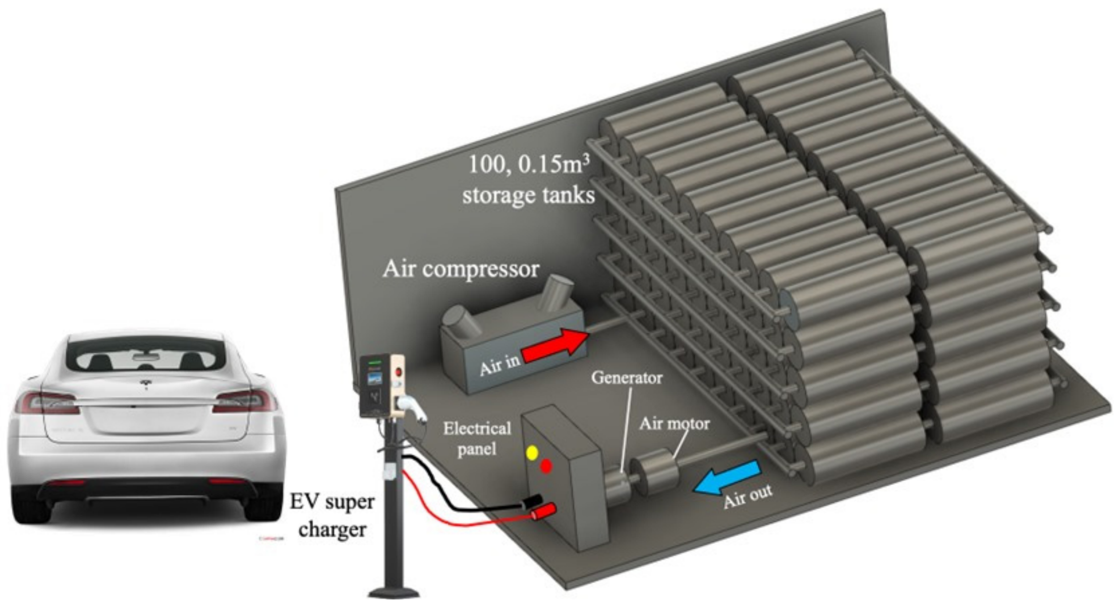

Figure 5. Proposed Design of a CAES system with EV charging station.

Future EV charging stations may include Green Hydrogen Storage (GHS) systems [83] as a novel way to adopt more eco-friendly EVs. The surplus renewable energy is utilized by GHS to generate clean hydrogen through the process of electrolysis and afterwards stored for convenient use.

Battery-buffered charging represents an attractive and economically significant alternative in scenarios where grid enhancements are costly or slow. NREL's technical assistance case study revealed that substituting a necessary substation upgrade (around USD 3 million) with a battery-buffered DC fast-charging (DCFC) solution could reduce capital costs by approximately 65% and reduce project timelines by 2 to 5 years. Their analysis indicated incremental battery costs of roughly USD 400 to 1000 per kWh and proposed station sizing guidelines, suggesting hundreds of kWh; the example site required approximately 480 kWh to accommodate four 150 kW ports under the specified design-day demand. DOE/NREL guidance and recent evaluations indicate that on-site storage facilitates significant simultaneous power delivery while minimizing utility-side enhancements [84]. However, the trade-offs are clear: increased initial battery investment, maintenance complexity, and site selection challenges versus rapid deployment and enhanced renewable energy utilization when integrated with photovoltaic or wind systems. Complementary strategies (flywheels for pulsed high-power demands, fuel-cell backup for extended autonomy, or pooled V2G portfolios) provide unique power/energy and cost characteristics, making them optimally suited for particular applications (corridor DCFC, depot charging, or remote access) [85].

6. Discussion

The rapid adoption of EVs depends on standardized technical specifications. Brown et al. [86] claim that the adoption of EVs will decline without strict regulations guaranteeing compatibility, safety, and sustainability. Current regional protocols (SAE J1772/CCS in North America, IEC Type 2/CCS in Europe, GB/T in China, etc.) exhibit varying historical approaches; however, extensive interoperability is essential. International and national rules, such as the U.S. NEVI requirements, now necessitate ISO 15118 ("Plug & Charge") adherence, recognizing its open, global significance and its facilitation of bidirectional charging and safe authentication. In practice, advanced charging technologies (fast DC, wireless, V2G) rely on communication standards and standardized connectors for optimal functionality. Implementing these regulations across regions mitigates fragmentation for manufacturers and drivers and facilitates the implementation of innovative technologies such as V2G and grid-aware charging [16].

To advance beyond just descriptive examples, it is essential to analyze the fundamental causes and trends that influence the deployment of charging infrastructure across various locations. Although all major markets seek to enhance charging accessibility, the pace and form of implementation are significantly shaped by governmental frameworks, prevailing business models, and local grid conditions. For example, U.S. installations are directed by NEVI funding and a combination of OEM-led and utility-led networks, whereas Europe prioritizes cross-border interoperability through EU regulation, and China depends on centralized planning by state utilities. In contrast, Japan emphasizes resilience and early V2Grid demonstrations. Table 14 summarizes these differences by comparing deployment drivers, prevailing business models, and significant technical or policy barriers across regions.

Table 14. Deployment drivers and business models of EV charging infrastructure.

Region	Primary Deployment Drivers	Dominant Business Models	Key Grid/Policy Challenges	Example Initiatives
United States	Federal and state incentives (NEVI Formula Program), strong OEM involvement (Tesla, GM, Ford joining NACS).	Mix of utility-led networks (e.g., Duke Energy), OEM-led (Tesla Supercharger), and private operators (Electrify America).	Patchwork of utility regulations across states; high interconnection costs; ensuring interoperability across CCS and NACS.	NEVI-funded DCFC corridors, Tesla NACS opening to other OEMs.
European Union	EU Alternative Fuels Infrastructure Regulation (AFIR) mandating interoperability and minimum charger density; strong climate policy alignment.	Utility and energy company-led (Ionity, EnBW); growing municipal partnerships.	Ensuring cross-border interoperability; integrating high shares of renewable generation; high land/permit costs in dense cities.	Ionity pan-European HPC network; Germany's national tender for 1,000+ sites.
China	National mandates for GB/T, central planning by State Grid and China Southern Grid; strong subsidies for both vehicles and charging.	State-owned utility dominated (State Grid, Southern Grid), supplemented by private operators.	Balancing rapid EV uptake with regional grid capacity; ensuring quality and safety in ultra-fast chargers.	1.8M+ public chargers (2024), GB/T nationwide standardization.
Japan	Early government support for CHAdeMO; focus on disaster resilience and V2G pilots.	OEM–utility partnerships (TEPCO, Nissan); municipal resilience projects.	Transition from CHAdeMO dominance to multi-standard compatibility; declining utilization rates of older CHAdeMO units.	TEPCO–Nissan V2G pilots, CHAdeMO V2X applications.

Energy storage, including both mobile (EV batteries) and stationary systems, is essential for the integration of advanced charging into the grid. Bidirectional V2G, for example, utilizes stationary EVs as distributed storage to assist in load balancing during periods of peak demand or high renewable energy production. Likewise, co-located batteries or alternative storage methods like as CAES or hydrogen at charging stations can mitigate fluctuations and enhance resilience. The U.S. DOE investigation indicates that on-site battery buffering permits EV chargers to receive steady power at moderate rates and then discharge rapidly during car charging, facilitating fast charging even on limited grids. This "peak shaving" reduces the load on the power grid and enables continued charging during outages; however, it also increases capital cost. Policymakers and planners must evaluate the high initial investment of integrated storage against long-term advantages such as reduced grid enhancements and improved renewable resource use. Storage interactions shift EV infrastructure from passive loads to active grid participants; yet, achieving these advantages necessitates supplementary technology (power converters, control algorithms) and standards [87].

The interaction of standards, technology, and storage has evident policy and technical consequences. Policy frameworks are progressively formalizing interoperability; for instance, recent federal regulations link electric vehicle infrastructure funding to standardized hardware (connectors, communication protocols) and demand advanced features such as ISO 15118 for smart charging. These regulations seek to guarantee that drivers can charge consistently across networks and that infrastructure can expand effectively. The technical ramifications necessitate approved cybersecurity and public key infrastructure (PKI) systems to provide Plug & Charge, with open network protocols such as OCPP and OCPI for chargers. Simultaneously, the integration of storage necessitates an update of grid interconnection rules and incentives; for example, rate designs or subsidies may be required to promote the adoption of battery buffers or V2G systems at fast-charging stations. A coordinated effort from global standardization organizations to local regulatory authorities is necessary. Policymakers can assure that next generation charging infrastructure is safe, dependable, and capable of supporting renewable intensive smart grids only by matching technical standards with advancements in storage and grid control [16].

7. Conclusions

This review combines the current state of EV charging standards, technologies, and renewable-integrated storage, placing them within the 2024 market context: global EV sales approximated 17 million in 2024, and the worldwide EV fleet surpassed 58 million vehicles by the end of 2024, with the deployment of fast chargers and public charging facilities expanding rapidly yet unevenly across various regions. The leading market and energy analyses project sustained growth in vehicle electrification and electricity demand for transportation through 2030, while trends of battery-cell costs and rapid charger deployments will increasingly shift focus from vehicle availability to charger interoperability, grid effects, and storage-enabled solutions.

To translate these trends into resilient, scalable infrastructure the review identifies five urgent research priorities: (1) A comparative analysis of charging standards and protocol features across regions to mitigate fragmentation and enhance interoperability; (2) localized, quantified studies on grid integration and techno-economics for high-power charging, including the cost-benefit analysis of on-site buffering; (3) extensive multi-market trials of V2G/storage systems that quantify aggregated value streams and assess battery degradation impacts; (4) comprehensive validation of ISO-15118/PKI, roaming, and cybersecurity implementations among various vendors and governments; and (5) comprehensive lifecycle and cost comparisons for off-grid and hybrid renewable charging solutions across diverse climates. To address these drawbacks, coordinated cross-regional evaluations, standardized metrics, and regulatory instruments that match incentives for interoperability, storage deployment, and grid-aware charging are necessary.

Author Contributions

A.M.: conceptualization, methodology, writing—original draft preparation, writing—reviewing and editing; A.Y.: conceptualization, data curation, investigation, writing—original draft preparation; A.H.K.A.: methodology, writing—original draft preparation, writing—reviewing and editing, investigation; K.E.: methodology, supervision, writing—reviewing and editing, investigation. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No data was used for the research described in the article.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of the revised version of this work, the authors used OpenAI's Chat GPT and Grammarly in order to improve language and readability, with caution. After using these tools, the authors reviewed and edited the content as needed and took full responsibility for the content of the article.

Abbreviations

BEV	Battery Electric Vehicle
CAES	Compressed Air Energy Storage
CCS	Combined Charging System
CHAdeMO	CHAdeMO protocol
DCFC	Direct Current Fast Charger
DOE	U.S. Department of Energy
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
GB/T	Guobiao (China) standard
GHS	Green Hydrogen Storage
IEC	International Electrotechnical Commission
ISO 15118 (ISO/IEC 15118)	ISO 15118 vehicle–charger communication standard
NEVI	National Electric Vehicle Infrastructure
NREL	National Renewable Energy Laboratory
OCPI	Open Charge Point Interface
OCPP	Open Charge Point Protocol

OEM	Original Equipment Manufacturer
PKI	Public Key Infrastructure
PLC	Power-Line Communication
PV	Photovoltaic
PWM	Pulse-Width Modulation
SoC	State of Charge
V2G	Vehicle-to-Grid

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