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SURVEY

Unraveling the Smart Charging Technologies, Energy Sources, and Regulatory Standards for EVs

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ABSTRACT Electric vehicles (EVs) are anticipated to be pivotal contributors to the global energy transformation in the automobile industry, ignited by their rapid proliferation. However, the widespread integration of EVs requires rigorous research and synthesis in charging solutions and EV supply equipment to meet the expected performance and improve ancillary services. Analysing the current landscape of EV charging technologies, it is essential to accelerate EV adoption by incorporating advanced control strategies that mitigate negative impacts and improve charging efficiency. Thus, this study presents a meticulous review that culminates in a curated anthology of 81 pivotal articles, with a predominant emphasis on charging EVs and associated technologies. The findings reveal extensive potential in this domain with our rigorous scrutiny of studies uniquely integrating all critical EV charging technologies, including their taxonomy, on-board and off-board charging infrastructures, and the global standards, and future research directions. The revelations of the study elucidate the prevailing paradigms within the EV research nexus, charting a course for future scholarly pursuits and practical applications.

INDEX TERMS Charging infrastructure and standards, regulatory frameworks for EVs, conductive and inductive charging.

I. INTRODUCTION

Electric vehicles (EVs) are transforming global transportation by offering a cleaner and more sustainable alternative compared to internal combustion engine (ICE) vehicles. The concept of EVs is not new: Between 1897 and 1900, they comprised approximately 28% of all automobiles, long before their modern resurgence [1]. However, the advent of ICE vehicles, powered by low-cost oil and technological advancements, quickly dominated the market, causing EVs to be a historical footnote [2]. Today, with the harmful consequences of air pollution and environmental degradation becoming increasingly visible, EVs are emerging as a crucial answer to reach the Net Zero (NZ) goals [3], [4], [5]. According to the Environmental Protection Agency (EPA) [6], the transportation sector contributes significantly to greenhouse gas (GHG) emissions, contributing 29% of the total GHG emissions in 2022. Therefore, a massive shift to EVs as compared to ICE has the potential to drastically reduce this percentage. Breakthroughs in technology, such as

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TABLE 1. Comparison with other studies.

Description	[17]	[18]	[19]	[20]	[21]	This Paper
The latest trends in charging technologies	✓	✓	✓	X	X	✓
Standards and Regulations for charging	X	X	✓	X	✓	✓
On-board charging resources	X	X	X	✓	✓	✓
Off-board charging resources	X	X	X	X	X	✓
Open issues and future prospects	✓	✓	✓	✓	X	✓

improved battery performance, charging infrastructure, and energy management systems, have further improved EVs widespread adoption.

EV charging systems can be evaluated using a variety of criteria, including battery charging technique, power flow guidance, usage of on- and off-board chargers, and power supply technology [7]. EV supply equipment (EVSE) is a critical component of a charging system that facilitates the power transfer between the EV and the grid [8]. EVs can be integrated into the grid using a combination of on- or off-board chargers that use alternating current (AC) or direct current (DC) [9]. Most commercial on-board chargers support unidirectional power flow, commonly known as grid-to-vehicle (G2V), which is recommended due to its simplicity, reliability, affordability, and simple control technique [10]. Bidirectional chargers, on the other hand, offer vehicle-to-grid (V2G) capabilities, which can return power to the utility grid [11], [12]. EV chargers incorporate sophisticated charging algorithms to allow optimal charging/discharge and adaptive power distribution by connecting to the EV and the electrical grid, thus improving the energy efficiency of the charger and reducing the load on the electrical grid [13]. The Institute of Electrical and Electronics Engineers (IEEE), the International Electrotechnical Commission (IEC), and the Society of Automotive Engineers (SAE) have recently greatly improved fast charging standards for AC and DC charging [14]. General accepted standards, along with regulatory regulations and standards, have been implemented for sustainable grid operation and to reduce negative consequences on the transmission network [15]. Rapid and ultra-quick charging stations attract attention since they are capable of charging the pack of batteries in a shorter time at higher levels of electricity [16]. Therefore, an exhaustive review of EV charging methods, on- and off-board couplers, their safety parameters, and standards is needed to prevent imminent problems and offer solutions.

A. PURPOSE OF THIS STUDY AND RESEARCH QUESTIONS

Over the years, extensive research has been conducted on various aspects of EV technology, covering topics such as battery advancements, charging infrastructure, energy management, and policy frameworks. However, the rapid evolution of EV technology, coupled with the urgent need for sustainable transportation solutions, necessitates a comprehensive and up-to-date survey that consolidates recent advancements and identifies emerging challenges. This study aims to bridge this gap by providing a state-of-the-art comparative analysis of existing EV research, highlighting key innovations, technological limitations, and future research directions. A summary comparing our findings with prior studies is presented in Table 1. Unlike previous surveys that focus on isolated aspects of EV technology, this work takes a holistic approach by examining both technical and infrastructural challenges, regulatory considerations, and the evolving role of EVs in smart grids and energy ecosystems.

1) What are the current charging methods used?
2) What sort of charging couplers are currently utilized in the EV infrastructure?
3) What are the various on-board energy sources?
4) What are the various off-board energy sources?
5) What are the standards for charging?

To the extent of our knowledge, this investigation represents a pioneering endeavour focused on developing an EV charging taxonomy and synthesizing the expansive framework encompassing various related facets.

The paper is structured as follows: Section II presents the descriptive analysis of EV charging methods to address the answers to 1. In this section three charging methods: conductive charging II-A, inductive charging II-B, and battery swapping II-C are discussed in details. Section III covers the currently used charging couplers for EV infrastructure. Conductive and inductive charging couplers are studied in III-A and III-B, respectively. Section IV covers available on-board energy sources focused on different batteries, capacitors, and available cells. Section V covers seven different types of off-board energy resources. Section VI provides a comprehensive review of research questions pertaining to the EV charging standards and regulations. EV charging technology standards are covered in section VI-A, followed by the coupler/connector standards in section VI-B and finally the communication standards in section VI-C, respectively. Finally, a general discussion of future work is presented in sections VII, followed by a conclusion in section VIII. The taxonomy of this study is illustrated in Fig. 1.

II. EV CHARGING METHODS

An EV charger is a device that converts the power from an external source into an energy form suitable for the battery system [14]. There are typically three primary ways to charge EVs: (i) conductive charging, (ii) inductive charging, and (iii) battery swapping. As conductive charging is much more affordable and effective, charging station operators prefer it [22]. However, several development

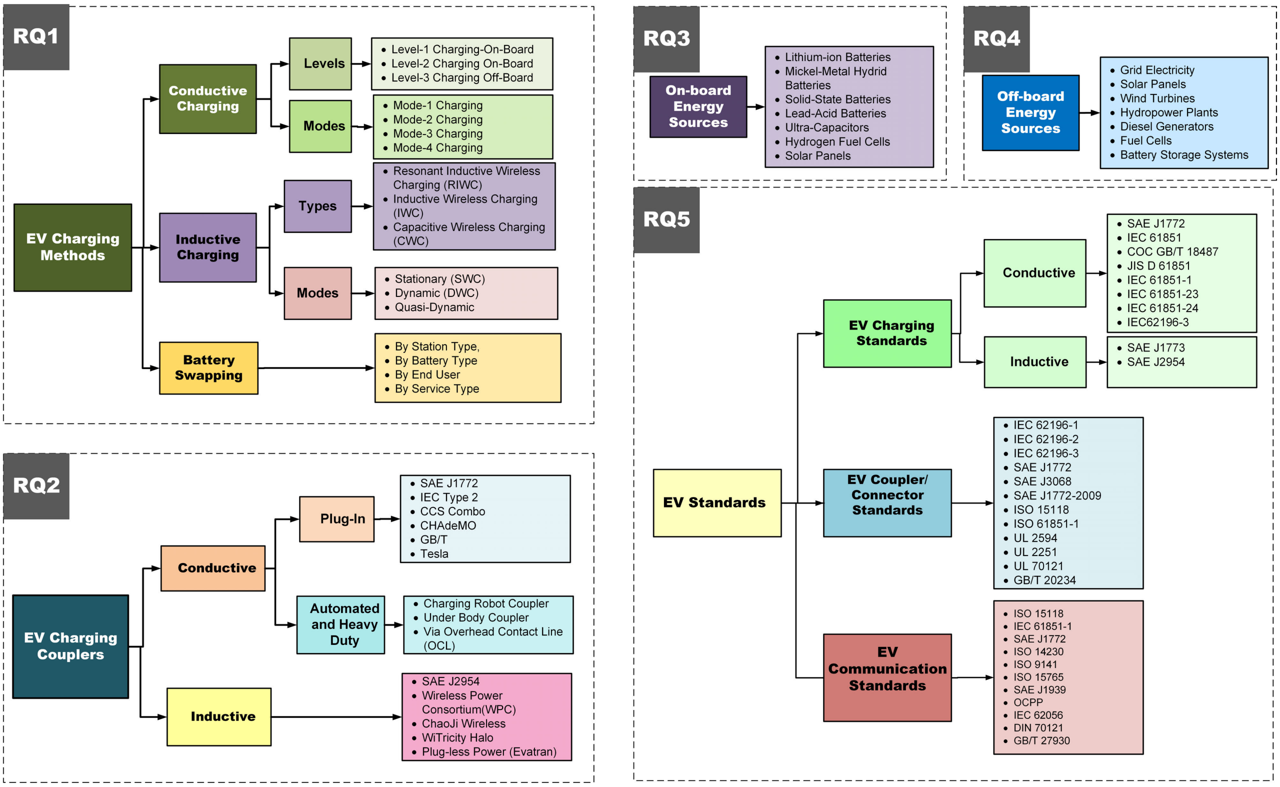


FIGURE 1. A comprehensive taxonomy of EV charging methods, couplers, energy sources, and standards: A visual guide to smart charging technologies.

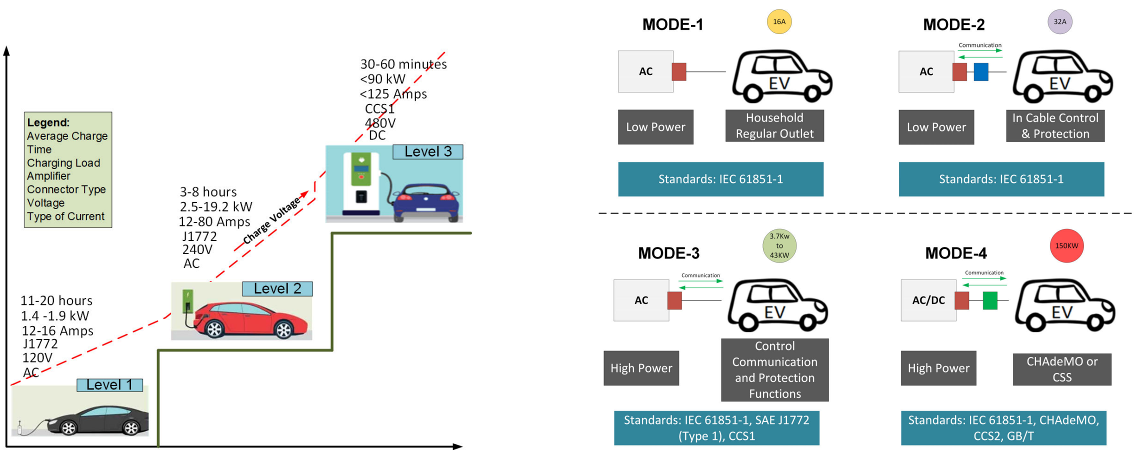


FIGURE 2. Levels and modes of EV charging.

initiatives are enhancing inductive charging, as it improves user convenience [19], [23]. For battery swapping to be conceivable, standardized battery measurements and internal connections are required, and batteries from every manufacturer would have to be almost the same in terms of dimensions, form, and kind [24]. This severely restricts the freedom of design and narrows the battery placement options.

A. CONDUCTIVE CHARGING

Conductive charging systems utilize charging cables and connectors between the EV connector and the internal charge unit [21]. The EV's battery receives electrical power from the charging point through these connectors [19], [21]. There are three different charging levels and four different modes of charging as shown in Fig. 2. Let us discuss them in detail in the relevant sections.

TABLE 2. Summary of EV charging levels [18], [20], [25], [27], [28], [29], [30], [32], [33].

Parameters	Level 1	Level 2	Level 3
Current	AC	AC	DC
Voltage	120 V	208V-240V	400-1000V
Charging Power	1.3-2.4kW	2.9-19.2kW	50-350kW
Time (EV)	40-50 hours	4-10 hours	20 min - 1 hour
Time (Hybrid)	5-6 hours	1-2 hours	N/A
Power Source	Wall outlet	In-house and Public charger	Public charger
Connector Types	SAE J1772	SAE J1772, Tesla	CCS, CHAdeMO, Tesla
Grid Voltage	120 VAC, 230 VAC	240 VAC, 400 VAC	208-600 VAC /VAD
Power Limits	≤3.3 kW	3.3 kW - 20kW	>50 kW
Issues	Slow charging, limited power, home-use only	Moderate charging, installation costs, grid load, charging availability	Rapid charging, costly infrastructure, battery degradation, inconsistent compatibility, grid stress
Application	Home, Offices	Home, Offices, Public	Public Only

1) LEVELS

- Level-1 on-board: This technique is also known as *home charging*. A grounded electrical outlet and a proper cord set to transfer current via an internal charger is used. This level supports connection to the existing outlets [20], [25], [26]. However, it uses a single-phase AC charging approach that integrates the motor and inverter within a dual-inverter system [27]. This method aims to enhance the voltage state of the AC charging compared to conventional chargers.
- Level-2 on-board: This charging point charges the EV rapidly than a Level-1 charger. An EV must be equipped with an on-board charger capable of using an AC EVSE for power. The term "fast AC charging" denotes charging at levels of 7kW (32A single-phase) or 21kW (three-phase). The main EV charging technique involves extending AC electricity from the electrical source to power an EVSE-specific on-board charger. Most significantly, home, office, and public charging stations can utilize this level [20], [28]. This specific charge level is used where a single economically priced charger can serve multiple residential buildings or families. A two-level optimal hybrid EV charging approach by adaptive-equivalent consumption minimization and dynamic programming was developed in [29].
- Level-3 off-board: This is also referred to as DC rapid charging. It provides high-power DC directly to the vehicle's battery, allowing for much quicker charging in comparison to Level-1 and Level-2 connectors. Level-3 chargers are often found in public or commercial locations and can quickly charge an EV to 80% in about 20-30 minutes, making them ideal for long journeys and emergency charging [28]. A suitable off-board charger can provide energy to the conductive charging system architecture. The DC power source can vary from AC Levels-1 and -2 to extremely high power levels, capable of recharging an EV battery to over 50% in as little as 10 minutes. There is a wide range of power levels at which an EV battery can be charged [30]. To accomplish rapid DC fast charging, Levinson et al. [31], [32] introduced an algorithm for an off-board converter using three phases to regulate the maximum power level electricity grid from an exaggeration induced by the heightened demand for EV fast charging. Nonetheless, apartment building occupants can efficiently utilize Level-2 charging at a minimal cost of charging [33].

Finally, Table 2 presents summary of charging levels.

2) MODES

The charging method specifies the protocol for a safe interlink between the EV and the charging facility. Globally, these standards are uniform [34]. A potential method to recharge an EV is to connect the on-board charger via the main AC supply system. Using an off-board charger to deliver a DC supply is an additional EV charging technique. Fast charging could be achieved by using a high-power charging infrastructure [35].

- Mode-1: It is commonly utilized for home charging [34], [35]. The EV is connected to the AC power supply by employing the standardized electrical sockets at the supply edge that use both power and protective ground conductors. To operate in this mode, the electrical configuration must adhere to safety requirements and possess an earth leakage protection system. An electrical circuit breaker of 10-A and sockets are essential for the earthing system to provide overload protection and prevent accidental contact [33], [35], [36], [37].
- Mode-2: The EV is connected to the electrical grid through common household outlets. To recharge, an earthing cable must be installed along with a network, that is either single or three separate phases. There is an internal safety feature on the cable. This particular method is costly as compared to mode-1 [36], [37], [38]. Mode-2 charging is accomplished within the home using a common power outlet and an additional cable EVSE, frequently referred to as an *occasional cable*, which typically comes with an EV from its maker. The in-cable control box or in-cable control and protection device (IC-CPD), which has an integrated current limit, is the "box" on the cable. Similar to a charge point, the IC-CPD can exchange data with the EV and has

protection inside of it that would not be present in mode-1. The maximum charging current for a typical domestic outlet is 10A. This restriction to 10A leads to an aggregate charging rating of 2.3kW [37]. Overheating and potential fire could occur from a frequently used socket if the charging current is not restricted to 10A [39], [40], [41].

- Mode-3: Through a designated socket, plug, and circuit, the EV is directly attached to the infrastructure. Surveillance and protection features are reinstated in the installation permanently. This is the only charging option that conforms to the regulations governing electrical connections. It enables load-shedding, which extends the duration of EVs that can be charged along with the operation of electrical household appliances [38], [41]. It has a higher power output compared to mode-2. In this mode of charging, a control circuit extends to operate devices, and the EV remains permanently linked to the AC power supply via a specialized EVSE [24].
- Mode-4: An external charger is used to connect the EV to the primary electrical infrastructure. The vehicle charging cable and control and protection components have been permanently embedded in the integration [31], [40]. Moreover, in this mode, the DC charging station is able to be used for home or public charging. The EV charger is a component of the charging point, rather than the EV itself [24]. During this charging mode, an off-board charger connects the EV to the AC network, and the pilot control operation applies to equipment that is connected to the AC supply [42].

B. INDUCTIVE CHARGING

This is a new technology that transfers power from a charging facility to an EV without the use of physical connectors. It operates via electromagnetic transmission and is also referred to as inductive power transfer (IPT), wireless power transfer (WPT), contactless power supply (CPS), or contactless energy transfer (CET) [43]. The electromagnetic field produced by the swapping current affects the EV's receiver, which is also made of wires, causing an induced current to pass through it to replenish the battery. This system comprises a setup of a charging pad, which serves as the main component placed at the power outlet, and a receiving pad, which is the secondary component placed underneath the EV. Water and non-metallic substances such as flagstone, asphalt, and other materials are used for energy transfer [18], [28], [44]. This unique method carries power over an inadequate air gap, resulting in a frictionless charging experience [38].

1) TYPES

Understanding these types is critical because they influence the prospects of electric transportation, increase user convenience, and promote universal adoption [44], [45]. Each type is designed to meet certain charging requirements and operational conditions.

- Resonant Inductive Wireless Charging (RIWC): RIWC is a revolutionary technique employing magnetic resonance technology. In contrast to conventional inductive charging, which depends on the charger and receiver being close to one another, RIWC functions more efficiently at longer distances [43], [45]. Resonant inductive coupling, in which both the transmitting as well as receiving coils are set to a certain resonant frequency, is used to accomplish optimal energy. This increases the transmission of energy over an air gap. The technology makes it possible to charge contactless without requiring physical connectors, which is especially useful for open spaces and urban settings where accessibility and usability are crucial. Roadways, driveways, and garages may all be equipped with RIWC systems, which enable EVs to recharge while parked or moving. RIWC offers a more flexible and user-friendly charging solution in EVs, thus has the better potential for development [46].
- Inductive Wireless Charging (IWC): In IWC wireless energy transfer occurs when the AC passes via the primary coil, producing a magnetic flux that oscillates and enables an electrical current that circulates through the secondary coil. The 50kW CET system for charging large EV batteries was developed in [46]. A hybrid system that combines the propulsion system and the CET system is currently under development. Despite early reservations, this technology offers exceptional energy transfer efficiency even in larger air gaps between the transmitter and the EV load receiver [46], [47]. A secondary induction coil within the mobile device records energy from the field having electromagnetic parameters and converts it again into electrical power to recharge the battery pack. Induction chargers function by utilizing an induction coil embedded in a charging base to generate an alternating electromagnetic field. The proximity of the two induction coils forms an electrical transformer. Resonant inductive coupling in the charging system enables greater distances between the sender and receiver coils. To reduce the weight and resistance caused by the skin effect, this resonant system has been improved by adding a movable transmission coil and using alternative materials for the receiver coil, such as aluminum or silver-plated copper [48].
- Capacitive Wireless Charging (CWC): By using electric fields instead of magnetic ones, CWC, is a technique for transmitting electrical power between two objects. A pair of conductive plates is used in this technique: a transmitter plate that is attached to an electrical source and a receiving plate that is attached to the item that needs to be charged. Energy is transferred wirelessly when an AC is delivered to the transmitter plates [47], [48]. This causes an electrical field that oscillates, causing a displacement current to be induced

in the receiver plates. CWC has several benefits over inductive techniques, including the capacity to recharge via non-metallic materials such as plastic or glass and less electromagnetic interference. It is especially helpful in applications where seamless design and limited space are essential. For effective energy transfer, CWC usually needs exact alignment and near-distance transmission device and receiver plates. The effectiveness of CWC is improved by development in materials and circuit design, which will result in a viable technology for the upcoming wireless charging applications [5], [45], [49].

2) MODES

There are three charging modes: stationary, dynamic, and semi-dynamic. Each mode uses electromagnetic induction to WPT, although their diversity depends upon EV position, charging time, and operating conditions. EVs can use one of three WPT modes designed to accommodate a variety of charging conditions and mobility needs.

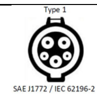
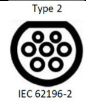
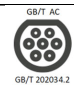
- Stationary Wireless Charging (SWC): SWC refers to the method of charging an EV while it is parked and inactive for an extended period of time at a fixed location. SWC's technology is evolving [43]. With SWC, charging is much more secure and convenient. With regard to vehicle operation, charging station assignment, charging time and frequency, SWC and conventional plug-in conduction charging are identical. Because their batteries have a short range, EVs require additional charging sessions to travel farther [45], [46]. Technologies that store and accumulate energy for later use are known as energy storage systems. Rechargeable batteries, an electronic management system, an inverter, and a thermal framework are the primary components of an SWC. An option for using the stored energy is to power a particular facility or an electrical grid. Batteries of a stationary repository are coupled to a renewable energy generator, such as solar or wind power.
- Dynamic Wireless Charging (DWC): The term DWC refers to the concept of wirelessly charging an EV when in motion. This concept was originally developed at the University of California, Berkeley [50]. Researchers from the Korea Advanced Institute of Science and Technology created the initial release for the sale of dynamic wireless charging technology, called online (OL)EV [51], at the beginning of 2009. The receiving component in DWC is positioned atop the EV body frame, and the transmission components are mounted on a minuscule pavement patch to supply charging for the moving EVs. The assortment of inductive wires or circuits beneath the road surface provides power to the vehicles that use the system [38], [52], [53]. Due to high costs, the technology's commercialization attempts have failed due to its low efficiency [54].
- Quasi-Dynamic Wireless Charging (QDWC): The term QDWC refers to a charging method that incorporates some modification of the dynamic or real-time charging parameters to optimize the charging process based on variables such as, for example, the conditions of the grid, the price of electricity or other pertinent variables [55]. It is categorized as either fully dynamic or real-time charging, where parameters are continually modified based on changing conditions, or static charging, where parameters remain static through the charging session. In QDWC, to reconcile the EV owner's needs, the power grid, and potentially other stakeholders, the charging system may periodically evaluate outside variables and perform adjustments to different parameters such as charging rate or voltage. This strategy seeks to optimize the charging process's effectiveness, dependability, and affordability. One potential solution in a quasi-dynamic charging system would be to factor in the daily fluctuations in electricity prices and modify the charging rate accordingly, allowing EV owners to take advantage of cheaper periods [56]. As an alternative, it might react to grid conditions and modify the charging rate to prevent overloading the power grid at times of high demand [57]. To achieve an equilibrium between simplicity and productivity, the QDWC concept allows for some degree of flexibility and optimization in EV charging without the ongoing adjustments seen in fully dynamic systems [55].

C. BATTERY SWAPPING

The third alternative involves swapping out depleted batteries for substitutes at an exchange station. Battery swapping also known as battery switching, is a technology used in EVs that enables them to quickly swap out a fully charged new battery pack for a discharged one, saving time compared to charging the vehicle at a designated point [58]. The potential of battery swapping to transform electric transportation and offer a workable and expandable solution for diverse automotive market segments is highlighted by its versatility across different vehicle types [59], [60]. Battery swapping is used frequently in applications involving Forklifts that are powered by electricity [59]. With about 11, 000 GoStations in Taiwan and 250 in Mainland China, The largest network for electric moped battery swapping is presently operated by the Taiwanese electric scooter company Gogoro [61]. The Chinese luxury manufacturer Nio is the only noteworthy operator of automobile battery-changing facilities for consumers. The procedure takes three minutes from beginning to end, and the company has developed about 2250 battery-change units throughout Europe and China [59]. Initiatives were made by Tesla and Renault as well. Generally, battery swapping will depend upon the station, battery type, end-user, or service provider. These techniques are explained below:

- By Station Type:
  - Manual Swapping: This method replaces the battery manually by individuals or technicians rather than

TABLE 3. Summary of region-wise EV charging inlets [15], [19], [26], [64], [66], [68], [69], [70].

Region	Connector	Pins	Protocol	Power	Levels	Range/Hour	Outlet	Image
North America	SAE J1772 (Type 1)	5	PWM	19.2 kW (AC)	Level 1, Level 2	10-50 miles	L120V (L1), 240V (L2)	
North America	CCS1 (Combo 1)	7	PLC	350 kW (DC)	Level 3, (DCFC)	180-240+ miles	400V-, 1000V DC	
Europe	Type 2 (Mennekes)	7	PWM	43 kW (AC)	Level 2, Level 3	20-75 miles	240V (L2), 400V (L3)	
Europe	CCS2 (Combo 2)	9	PLC	350 kW (DC)	Level 3, (DCFC)	180-240+ miles	400V-, 1000V DC	
Japan	CHAdeMO	10	CAN	400 kW (DC)	Level 3, (DCFC)	180-240+ miles	400V-, 1000V DC	
China	GB/T AC	7	CAN	43.5kW (AC)	Level 2	20-75 miles	240V, 400V AC	
China	GB/T DC	9	CAN	4900 kW (DC)	Level 3, (DCFC)	200-300+ miles	400V-, 1000V DC	
Tesla (Global)	Tesla (NACS)	5	Proprietary	250kW (DC)	Level 2, Level 3,	150-250 DC	240V (L2), 400V-1000V DC	

utilizing sophisticated machinery. When an owner or driver brings their EV to the station, technicians manually remove the discharged power battery and change it out for one that is completely charged. During this procedure, it might be necessary to secure the replacement battery, carry out quality inspections, and guarantee correct installation [22]. Compared to traditional charging methods, the EV owner can drive again after the swapping is finished because the power unit is completely charged. Although it was investigated in the initial stages of the formation of EVs, manual battery swapping has encountered difficulties. As a result, automated or semi-automated solutions have become more popular to address effectiveness as well as security challenges.

  – Automatic Swapping: In this method, the charging stations use a robotic system to deactivate the EV's depleted battery and change it out for a fully powered one. Immediately as the EV pulls into a designated station, an automated system finds and replaces the battery with a fully charged one [59].

- By Battery Type: Techniques for battery swapping can use a variety of battery classifications, for instance, hybrid nickel-metal and lithium-ion batteries. At a battery swapping station, a fully charged lithium-ion or nickel-metal hybrid battery is swapped out for a depleted one. The versatility of the switching strategy in supporting various battery compositions promotes the growth of EV technologies [22], [62].
- By End User: For EVs, battery swapping is a flexible solution that can be used by end users of both passenger and commercial vehicles. This strategy is especially pertinent to passenger cars, where easy and quick recharging is essential to improving the user experience and promoting the general use of electric mobility. Fleet managers can continue operating their vehicles continuously by using battery swapping as a time-effective substitute for extended charging times for commercial vehicles, such as electric delivery vehicles and buses.
- By Service Type: EV battery swapping services can be designed using a variety of service models, such as pay-per-use and subscription. Under a subscription-based model, customers pay a set amount each month to receive access to a predefined number of battery swaps over a predetermined period. This strategy fits the needs of consumers who value a set, recurring

cost for the maintenance of their EVs by providing predictability and convenience. Conversely, a pay-per-use model offers flexibility to users who might not need to replace their batteries frequently by charging them only when they swap them out. This payment model is appropriate for users who have different usage patterns or who would rather pay for the service in more discrete ways [22], [61].

III. INFRASTRUCTURE FOR CHARGING COUPLERS

Various EV charging connectors and couplers are available, each with special features and functionalities. Significant variations in the power rates, standards, and configurations of EV chargers and couplers are present in different regions. To prevent disputes and difficulties, manufacturers and regulatory organizations are working to ensure compatibility by developing universal standards and protocols [40], [63]. The summary of region-wise classification of the charging inlets is shown in Table 3. EV battery holds DC energy, grid power is provided as an AC electricity. Therefore, a conversion from AC to DC is required, which is achieved by the EV onboard charger. For DC fast charging, the charging station is required to convert AC to DC before being utilized by the EV. Because DC fast charging provides direct power to the battery than through the vehicle's onboard charger, it enables a faster charging solution [15], [19], [26], [32]. In this section, the charging connectors and couplers that are currently utilized in the EV infrastructure will be covered.

A. CONDUCTIVE CHARGING COUPLERS

The main component of is the electrodes and can be further classified into two main systems, described hereunder:

1) PLUG-IN CHARGING CONNECTORS

There are six classifications of plug-in charging connectors, each designed to operate with a particular charging standard and power level. Each connector has a unique design, compatibility, and charging speed to meet regional needs.

1) SAE J1772: It is a standard EV connector extensively used in North America, offering a flexible and reliable option. It works with both Level-1 and Level-2 charging stations and comes with a single-phase electrical charging mechanism. To guarantee safe charging, the connector is designed to include safety parameters such as a ground pin and a locking framework. In May 2011, its parameters were updated to align with the IEC Type-1 coupler or IEC 62196 − 2 standard. Since AC battery charging systems are compatible with power sources and have a 19.2kW charging capability, they are widely used in the US, Canada, and Japan. This coupler features five pins in three different sizes and a circular diameter of 43.8mm [64]. The EV's control system can limit mobility while connected to the EVSE and notify the EV of the latch push key by using the proximity pilot detecting pin. One type of communication signal is through the control pilot pin. It is used to transmit additional data as well as the charging level information across the EV environment. The transmitted signal is employed to control the start/stop charging process, convey the permitted charging current limits, and detect the presence of an EV [26], [64].
2) IEC Type-2: The German business Mennekes introduced the Type-2 connector in 2009, typically referred to as the *Mennekes Type*-2. Its status as the industry standard for charging EVs has been cemented by its extensive adoption throughout Europe. The European Commission was recognized as a regulated charging coupler in January 2013 [65]. The same coupler is being used by Australia and New Zealand, two non-EU nations, while a comparable but distinct design is explained as Guobiao (GB)/T 20234 − 2. The IEC 62196−2 states that the original purpose of this coupler was intended for use with AC charging solutions. That indicates that it can be charged by an AC power supply that is either single-phase or three-phase of up to 7.4kW or 43kW, respectively. This type-2 coupler has three possible configurations [66], [67]. Furthermore, the type-2 IEC connection features a smooth side and a cylindrical 70mm size for use with mechanical alignment. Certain public EV charge outlets in Europe, Australia, New Zealand, and various other locations have socket outlets solely, whereas others provide charging cables. Additionally, a portable EVSE is also provided. This EV charging cable features a Schuko socket and a device for IC-CPD, enabling AC charging through a standard home outlet. It was designed in collaboration with Siemens and Mennekes [64].
3) Combined Charging System (CCS) Combo: Europe has access to DC fast charging, as in North America, with the CCS Combination 2 standard. Similarly to the J1772 connector of the CCS Combo-1, it combines the Type-2 connector with two DC rapid charging outlets [64]. The CCS Combo specification uses a single EV input to manage both AC and DC fast charging levels.
4) CHAdeMO: It merges dual DC-fast battery ports in addition to the Type-2 connector, much comparable to the CCS Combo 1 (J1772-2) across the United States and Canada [26], [66]. In 2021 and 2022, respectively, the complete versions of ChaoJi-2, (CHAdeMO-3.0.1) and ChaoJi-3 (CHAdeMO 3.0) were made public. Significantly, the IEC has approved the newly proposed specification 61851 − 23; 62196 − 3; and 62196 − 3 − 1 for the ChaoJi charging mechanism and coupler. In 2023, field testing of ChaoJi-2 (CHAdeMO-3.0.1) was combined with the deployment of Ultra-ChaoJi (CHAdeMO-3.0.1) and Ultra-ChaoJi (CHAdeMO-4.0) in Japan [40].
5) GB/T: A collection of national standards for connections used in a variety of industries, especially communications, electronics, and EVs, is commonly referred

to as the GB or T standard connector. The GB/T series, which was established by the Chinese Standardization Administration, specifies the mechanical, electrical, and physical characteristics of connections to guarantee safety and interoperability. The GB/T-20234 standard specifies connectors for EV charging and includes various voltage and current requirements [68]. The China electrical charging standard (GB/T 20234.2 – 2015) defines cables having Type-2 male plugs at both terminals and female plugs on EVs, as well as unique control signaling, which is different from the rest of the world [19]. In addition, the third part of the GB/T-20234 standard contains the fundamental prerequisites, functional definitions, type components, features, and parameters for EV charging. GB/T-20234.3 – 2015 contains couplers working in charging mode-4 and connection mode C, with maximum voltages and peak currents of 1000V DC and 250A DC, respectively [66]. With the support of the governments of China and Japan, the CHAdeMO Organisation and CEC worked on developing a new global retroactive DC electrical charging standard that is fully compatible with the existing GB/T and CHAdeMO standards. At the CHAdeMO summit, a new GB/T-CHAdeMO coupler prototype was unveiled with a charging capacity of as much as 900 kW at 1500 V [19]. ChaoJi is the formal term for the forthcoming standard for EV chargers. ChaoJi standard will interface with EV charging devices over the CAN, comparable to its predecessors. This collaborative effort would culminate in a single, harmonized standard [15], [16], [26].

6) Tesla: This coupler is a unique charging interface made exclusively for Tesla EVs and is also referred to as the Tesla charging connector. The minuscule and sleek design of Tesla's connector, which combines AC and DC plugs into a sole socket, is widely recognized. The Tesla-developed connector is used by Tesla automobiles in North America for both rapid charging DC and at-home charging AC. Other parts of the world, notably Europe as a whole, have Tesla vehicles employing the more popular CCS plug [26]. The company's extensive charging network includes the Tesla EV coupler, which provides simple but efficient energy transmission for Tesla EVs. The firm now offers four EV models in its lineup, after the 2008 Roadster as its first: the Roadster 2020, Model-S, Model-3, Model-X, and Model-Y [69]. As a result, the US variant is also offered for sale in Mexico, Canada, Taiwan, and Japan, and has the exclusive Tesla inlet. Moreover, the Tesla offered for sale in Europe, on the other hand, is equipped with a Type-2 port or, more advanced, a CCS Combo-2 connector. Lastly, China has a twin inlet described as AC GB/T and DC GB/T inlets. With the installation of its own EV charging stations throughout the globe, often referred to as Tesla Superchargers or Tesla Megachargers thus the Tesla standard is gaining traction. Moreover, the 2.4kW, 120V trickle, 19.2KW, and 144kW 480V rapid charging rates are offered by these EV charging stations [69]. With a single connection, all three of these levels and frequencies are possible, enabling driving ranges of 3 to 273km/h of charge [70].

2) AUTOMATED AND HEAVY DUTY EV CHARGING CONNECTORS

These automated and heavy-duty EVs (HEV) can be divided into three types of charging connectors. The details are as follows:

1) Charging Robot Coupler: The most sophisticated and popular charging technique for HEVs is the charging cable method, which is the foundation of the passive conductive charging system that uses charging automation. This system requires a transformer and a rectifier in addition to the conductor, which can be placed inside or outside the EV. The HEV can be charged using DC, AC, or both simultaneously, depending on the setup. Currently, 500kW DC and 43kW AC of charging power are achievable. Even greater charging power over a megawatt will be possible by using the megawatt charging system that is presently being developed [71]. These couplers use robots that are outfitted with camera-based recognition to align and connect charging plugs. These robots use data about the particular vehicle, for instance, the precise location of the outlet for charging and the total amount of electricity required. The charging robot uses this information to align the charging connector with the charging socket, insert it into the connector, and then take it out of the socket. The accuracy of the robot's vision, control, and mobility systems, as well as the tolerance ranges of its components and the surrounding temperature, vibrations, and environmental factors, all affect its accuracy. Prominent firms in this domain comprise ROCSYS, Siemens, and Stäubli, all of which have made noteworthy progress. Stäubli's quick charging connector system delivers more than a MW of power for demanding conditions, Siemens' prototype gives up to 300kW of energy for charging tested with EINRIDE, and ROCSYS' robots are utilized by numerous businesses and at public facilities in the USA [19].
2) Under Body Coupler: A static or movable vehicle as well as a stationary or movable ground component, makes up an underbody-coupling system. The vehicle segment is fastened with the vehicle's underside, while the ground segment is integrated into or set on top of the charging point. The ground and the vehicle segment need to line up to allow the vehicle to be charged. For charging systems, the maximum amount of misalignment is measured at ±150mm off the ideal

parking placement over the axes of the car [24]. Assistance systems improve parking precision, and with the help of particular interface architectures and guidance systems, the electrical interfaces need to be physically joined once they are aligned. A voltage regulator, transformer, transmission system, and control system are also needed for the charging technology. Under the AC/DC Project, Volterio's underbody-coupling system is being tested in Graz, Austria for electric passenger vehicles. It has attained Laboratory Testing of Integrated and Semi-Integrated Systems (TRL-5), signifying validation in a relevant context. TRL-5 is also possessed by comparable systems from Fraunhofer IVI as well as Schunk Transit Systems, which were tested in the AULA Project and will be showcased in the Mega-Laden Initiative for HEVs. On the other hand, Elonroad's system achieved TRL-7 after being evaluated by an end user in a working context [72].

3) Overhead Contact Line (OCL): Electric buses and trucks are the main applications for the OCL EV charging system, which involves charging the vehicles using overhead power lines while moving or at predetermined pauses. Pantographs or other such devices installed on the vehicle's roof and connected to overhead electric cables are used in this manner to extract electricity. Similar to conventional trolley bus or tram systems, the system's continuous power supply negates the condition for sizable onboard batteries, thereby enabling greater operating ranges between recharge stations. Three pilot projects titled, "Field Test E-Highway Schleswig-Holstein", "eWay Baden-Württemberg", and "Electrified Innovative Heavy-Duty Transport on Autobahns" were developed in Schleswig-Holstein, Baden-Württemberg, and Hessen, respectively. These projects evaluate the viability of electric heavy-duty trucks that directly take electricity while driving via OCL. These lines are connected to trucks with pantographs, allowing for continuous charging and lowering dependency on fossil fuels. Every project assesses this technology's effectiveness, scalability, and performance in real-world scenarios across many geographies and terrains. Furthermore, Siemens developed the technology that is used in these projects. A pantograph is a component of this technology, can connect or disengage with the OCL reaching up to 90km/h, and will cut off on its own if the vehicle swerves or indicates [24]. High efficiency and the capacity to accommodate heavy-duty electric vehicles on lengthy routes with little downtime are the primary benefits of overhead contact line (OCL) charging. Because infrastructure may be incorporated into existing bus routes or dedicated lanes, it is especially advantageous in urban locations with well-established public transit systems. However, putting in overhead lines can be expensive and obtrusive, requiring a large investment and urban planning. Nevertheless, OCL EV charging is a practical and effective way for cities to electrify their fleets of public and commercial transportation while also lowering emissions and improving the sustainability of public transportation [19].

B. INDUCTIVE CHARGING COUPLERS

Portable electronics are powered by electromagnetic induction. The portable device does not have to line up exactly or establish an electrical connection with a terminal or connector positioned adjacent to a charging station or inductive pad. EVs require an onboard contactless charger, which adds weight to the vehicle. The different charging couplers are:

1) SAE J2954: The SAE designed AE J2954 as a wireless charging standard. It outlines the specifications for WPT systems, guaranteeing safety and interoperability with different manufacturers. The standard concentrates on effective and dependable charging with little electromagnetic interference and supports power levels up to 11kW. To enhance user experience to promote the broader use of electric mobility, SAE J2954 seeks to facilitate simple and convenient charging of EVs eliminating the requirement for physical connectors [40], [74].
2) Wireless Power Consortium (WPC): The WPC designed the Qi standard, which has been extensively utilized for wireless charging in commercial gadgets, but it may also be used for EV applications. The goal of WPC's EV charging initiatives was to provide a single, worldwide scalable infrastructure. The goal of the Qi norm for EVs is to make wireless charging simple and effective by utilizing the knowledge gathered from numerous millions of Qi-enabled consumer electronics. The strategy employed by WPC guarantees that EV charging may be widely available and user-friendly, which encourages the expansion of EVs [75], [76].
3) ChaoJi Wireless: With an emphasis on high-power wireless charging options for electric cars, ChaoJi Wireless is an emerging specification that was created mostly in Asia. It is made to meet the demands for instance buses and trucks by supporting power levels that are far greater than the present norms. To facilitate quicker adoption and more flexibility in the general public and corporate transportation sectors, ChaoJi Wireless seeks to offer a reliable and effective recharging service that can meet the demanding power needs of commercial EVs [77].
4) WiTricity Halo: WiTricity Corporation created the exclusive WiTricity Halo wireless charging system, which is renowned for its cutting-edge resonant inductive coupling technique. Possessing a maximum potential of 11 kW, the Halo system is intended to provide effective and powerful mobile charging for EVs. Convenience and compatibility are prioritized by WiTricity's technology, enabling smooth

integration across various car models and manufacturers. WiTricity Halo seeks to promote sustainable mobility and encourage the broad adoption of EVs by concentrating on intuitive and effective wireless charging solutions [78].

5) Plug-less Power (Evatran): Evatran created Plug-less Power, one of the initial wireless EV chargers to sell commercially. It allows EV owners to charge their vehicles hands-free using inductive charging technology. Power transmission levels range from 3.2 to 7.2 kW, the system is appropriate for commercial and residential uses. By rendering the charging procedure as simple as possible, Plug-less Power seeks to remove the inconvenience associated with plug-in charging, improving convenience and promoting the use of EVs [79].

IV. ON-BOARD ENERGY RESOURCES

There are seven on-board energy resources, let us discuss them in detail below.

A. LITHIUM-ion BATTERIES

EVs often run on lithium-ion batteries owing to their elevated energy density, high efficiency, and extended lifespan [28], [72], [73]. They serve as the main electrochemical component in batteries, enabling quick charging and discharging [11]. Because of their reduced weight, EVs run a longer range as compared to other energy resources [35]. However, they need to be handled carefully to prevent overheating. As this technology develops, it becomes more and more feasible for EV adoption to become mainstream.

B. NICKEL-METAL HYDRIDE (NiMH) BATTERIES

Although less frequent in contemporary EVs, NiMH battery packs stand out due to their durability and a longer lifespan than some other battery types. NiMH batteries were formerly a well-liked choice for hybrid vehicles [45]. When contrast lead-acid batteries, are more ecologically friendly and have a well-known energy density. Although NiMH batteries are usually inadequate and heavier compared to lithium-ion batteries, they are renowned for their resilience and capacity to withstand overcharging and severe temperatures. These days, its main uses are in some hybrid markets where cost is a critical factor [72]. NiMH battery may offer an alternative with benefits like endurance and affordability, as compared to lithium-ion batteries.

C. SOLID-STATE BATTERIES

They are novel innovations in this field as they employ solid electrolyte substances rather than liquid ones. Higher energy capability, quicker charging periods, and increased safety owing to fewer leaks and fire hazards are just a few benefits of this design [67]. It is anticipated that solid-state batteries would greatly increase the range of EVs and shorten their charging periods. They still need to overcome issues with scalability and manufacturing costs before they can be made commercially viable [74].

D. LEAD-ACID BATTERIES

It is one of the first variants of rechargeable batteries, which is still widely used in conventional automotive applications but is less prevalent in contemporary EVs because of its high weight and low energy density [67], [71]. They are utilized in certain EVs for auxiliary purposes including lighting, ignition, and starting despite these drawbacks. These batteries are cheap and produce a lot of power; however, they are less suitable for basic propulsion than lithium ion because of their shorter battery life and maintenance needs [67], [74].

E. ULTRA-CAPACITORS

Super-capacitors, often referred to as ultra-capacitors, are used in EVs to supplement conventional batteries by delivering brief energy bursts. Because of their ability to charge and discharge quickly and their ability to store energy electro-statically, they are perfect for operations that need high energy for brief stages, for instance, regenerative brakes and acceleration [72]. Ultra-capacitors possess less dense energy than batteries, which restricts their usage as the main source of power even if they have a longer cycle life and good power density. Rather, they are frequently used with battery packs to improve efficiency and performance [65], [67].

F. HYDROGEN FUEL CELLS

Hydrogen and oxygen combine chemically to develop just heat and water as a byproducts, which is how hydrogen fuel cells produce energy. Similar to traditional gasoline vehicles, this sustainable energy source has an elevated energy density and enables quick recharging [72]. Because of its effectiveness and advantages for the environment, fuel cells made from hydrogen are beneficial for longer-distance travel and heavier vehicles. Widespread adoption is hampered by the fact that the infrastructure needed for hydrogen generation, storage, and delivery is still in the development stages [20].

G. SOLAR PANELS

Solar panels are helpful for supplemental charging, particularly in isolated or off-grid areas, even if they normally cannot provide enough electricity to function as the main energy source [18], [72]. By extending EVs' range and lowering their reliance on grid power, solar panel integration with EVs might encourage the expansion of renewable and environmentally friendly energy sources' applications in transportation. There are many opportunities for EV applications as solar technology becomes more viable and efficient [67].

Finally, on-board energy sources are summarized in Table 4. Lithium-ion batteries outperform others in specific energy, energy density, and cycle life, but have moderate

TABLE 4. Summary of on-board energy sources for EV charging [11], [28], [35], [45], [67], [72].

Sources	Main Features	Drawbacks	Usage
Lithium-ion Battery	High energy density, long lifespan, efficient, rapid charging/discharging	Requires careful management	To avoid primary power source
Nickel-Metal Battery	Reliable, longer lifespan, environmental friendly compared to lead-acid	Reduced energy density and efficiency, substantial than lithium-ion batteries	Used in hybrid vehicles
Solid-State Battery	Enhanced energy compactness, rapid charging, time frame, elevated safety	High manufacturing costs, scalability issues	Emerging technology
Lead-Acid Battery	Inexpensive, high power output, widely available	Low energy density, heavy, shorter lifespan, maintenance required	Auxiliary functions
Ultra-capacitor	Rapid charging/discharging, extensive power compactness, extended lifespan	Low energy density and not suitable as alone primary power source	Complementary to battery systems.
Hydrogen Fuel Cell	Exceptional energy compactness, fast refueling, clean emissions (water heat)	Infrastructure for hydrogen production storage is under developed, high costs	Long-range and heavy-duty EVs.
Solar Panel	Renewable energy, reduces dependency on grid electricity, can extend EV range	Insufficient as the sole power source as it is dependant on available sunlight	Auxiliary charging, remote/off-grid

costs. On the other hand, lead-acid batteries are less expensive but lag in energy metrics and cycle life. Furthermore, it is also evident that Sodium-Nickel Chloride and NiMH batteries offer balanced trade-offs for various applications and exhibit moderate performance across all criteria [80].

V. OFF-BOARD ENERGY RESOURCES

The seven off-board EV energy sources covered in this section are:

A. GRID ELECTRICITY

The most popular energy source for charging electric automobiles is grid electricity. It includes using the electrical grid's AC, mostly through installed Level 1 and Level 2 outlets in public spaces, offices, and households. Because it leverages the electrical infrastructure that is currently in place, this approach is both broadly available and practical for EV owners. Controlling charging periods, such as postponing home charging, might lessen the effects of peak demand on the grid [81].

B. SOLAR PANELS

By turning sunshine into energy, solar panels provide an environmentally friendly power source for EVs. This renewable energy source may be utilized directly or indirectly through energy storage devices to charge EVs in public, commercial, and residential settings. Solar-powered charging stations contribute to a greener energy ecosystem by minimizing the utilization of petroleum-based fuels and emitting GHG wastage. When paired with battery storage systems, they work to provide reliable power availability [55], [82].

C. WIND TURBINES

EVs may be charged by wind energy, which is captured by wind turbines and utilized to create electricity. This renewable energy source may be used in off-grid configurations with storage options or incorporated into the grid [55]. This is an environmentally friendly and sustainable way to lessen the GHG emissions. To provide a steady energy supply for EVs, wind power fluctuation can be controlled by integrating it with other renewable sources as well as battery storage [83].

D. HYDROPOWER PLANTS

Electricity is produced by hydropower facilities using the flow of water, usually through rivers or dams. EVs may be charged by this renewable energy source, which offers a steady and dependable supply of electricity. The consistent and steady flow of electricity produced by hydropower facilities is crucial for preserving grid stability. This is essential for EV charging, particularly when the number of EVs rises and puts more strain on the electrical networks [85]. Moreover, Hydropower facilities are perfect for supporting extensive EV charging networks since they can produce steady power and assist in controlling peak loads. Hydropower integration with EV charging can improve the environmental sustainability of transportation networks [83].

E. DIESEL GENERATORS

n isolated or off-grid areas, diesel generators are employed for an alternative power source for recharge EVs. They are not eco-friendly, but they offer a dependable power source in the absence of other options. Diesel generators may be extremely useful in emergencies or places without enough grid infrastructure [82]. But because of their expensive fuel and significant pollutants, they are usually only used seldom and are not meant to be a main source of power. Instead, they are seen as a temporary or supplemental alternative [81].

F. FUEL CELLS

In fuel cells, the sole outcomes of the chemical interaction between oxygen and hydrogen are heat and water which allows them to produce electricity. When EVs are charged using this clean energy source, it offers a cost-effective and sustainable substitute for traditional power sources [55]. Hydrogen fuel cells are appropriate for use in both consumer and electrically-powered vehicles due to their substantial amount of energy and rapid refilling periods. Additionally, they are in favor of switching to a low-carbon power system [85].

TABLE 5. Summary of off-board energy sources for EV charging [55], [80], [81], [82], [83], [85].

Source	Main Features	Capacity	Share (%)	Impact	Cost	Key Features
Grid Electricity	Widely available varies by region	Depends on grid	High	Varies by source	Variable; usually lower	Most common source dependent on local grid
Solar Panels	Renewable	1 kW to 500 MW	Growing	Low	High initial lower O&M	Intermittent benefits from subsidies and incentives
Wind Turbines	Renewable	1 MW to 3 MW per turbine	Growing	Low	High initial moderate O&M	Intermittent suitable for windy areas
Hydropower Plants	Renewable and steady output	10 kW to 10+ MW	Significant	Low	High initial low O&M	Impact varies with scale can affect ecosystems
Diesel Generators	Reliable	10 kW to 2 MW	Declining	High	Moderate to high	Mostly used for backup high emissions
Fuel Cells	Clean and high efficiency	1 kW to several MWs	Emerging	Low	High initial lower O&M	Hydrogen production depend on source
Battery Storage Systems	Stores energy and easily scalable	1 kWh to 100+ MWh	Growing	Low	High initial moderate O&M	Useful for balancing intermittent sources

G. BATTERY STORAGE SYSTEMS

To be utilized for charging EVs, battery packs store energy from numerous sources such as the electricity grid, wind turbines, solar panels, and other renewable. Through the process of storing excessive power during shortages and leaving it considering excessive need, thus these devices improve grid stability [84], [85]. They make it possible to use renewable energy more effectively, which lessens dependency on fossil fuels and increases the capacity of EV infrastructure for overall sustainability. Battery storage is crucial for integrating energy from sustainable resources into the transportation sector [82].

Finally, the summary of energy diversification on off-board EV power sources is illustrated in Table 5. Liquid fuels, gaseous fuels, electricity, or hydrogen can be produced from energy resources such as oil, natural gas, biomass, coal, hydro, wind, solar, oceanic, geothermal, and nuclear. Moreover, the range of energy carriers and channels utilized to move towards cleaner vehicle technologies, such as electric and hydrogen-powered systems, is highlighted.

VI. EV CHARGING STANDARDS AND REGULATIONS

The EV charging standards and its regulation. We will focus on (i) charging technology standards, (ii) coupler/connector standards, and (iii) communication standards.

A. CHARGING TECHNOLOGY STANDARDS

To ensure that EVs operate efficiently in the coming decades, new charging protocols, global standards, and adequate infrastructure are required. There is a correlation between the price of the infrastructure necessary for the charging points and the hardware needs. There is a chance that some EV charging standards and regulations might make the charging infrastructure substantially more expensive and intricate than the electrical infrastructure that exists now [16]. Several international organizations are working to develop standards and regulations to facilitate the charging of EVs, for example, the IEEE, IEC, SAE, ISO, etc. [86]. Moreover, the general classification is described below and summarised in Table 6.

- Conductive Charging: The defined procedures and technical requirements that control the electrical and physical connections made directly between EVs and charging stations. These guidelines guarantee efficiency, safety, and compatibility in various EV models and charging systems. The two most well-known conductive charging standards are Type 1 and Type 2. The CCS, which combines Type 1 and Type 2 connections to enable AC and high-power DC charging over a single interface and foster interoperability, is another essential standard. These standards includes power ratings, connection design, communication protocols, and safety features that protect against current and heating issues [47]. To ensure access to an extensive selection of charging stations, conductive charging standards are fundamental elements to the seamless functioning of the entire EV ecosystem. This facilitates greater adoption and user comfort. Future developments can focus on improving power delivery capacities and including increasingly advanced safety and communication features to satisfy the growing need for fast charging facilities [19], [32], [68].
- Inductive Charging: Electromagnetic fields are used to transport energy from the on-ground charging component to the EV's. By eliminating the need for physical connectors, this technology improves convenience and reduces the wear and tear associated with conductive charging [87]. For inductive charging, the SAE J2954 standard is of vital importance due to its extensive procedures for WPT, of as much as 11kW, with plans to enable higher power levels in future expansions. Resonant inductive coupling, which transmits power via an air gap to ensure safe and effective energy transmission, is how the system functions. Several user convenience concerns are addressed by inductive charging, especially for those with physical restrictions or inclement weather [88]. There are still issues to be resolved, such as how to transport energy efficiently across different distances and how much it will cost to construct infrastructure. In order to maximize energy

TABLE 6. EV charging technology standard [19], [47], [68].

Category/Code	Scope	Key Aspects
	Conductive Charging Standard	
SAE J1772	Specifies requirements for WPT up to 11 kW	Enhances user convenience by minimising the requirement for physical connectors, supports safety measures and alignment
IEC 61851	Standard specifications for conductive charging systems	Covers different modes of charging (Mode 1 to Mode 4), addresses safety requirements and provides guidelines for communications
COC GB/T 18487	Specifies the basic requirements	Covers both AC and DC charging, defines communication protocols to ensures interoperability within the region
JIS D 61851	Specifies the basic requirements	Ensures interoperability, covers both AC and DC charging, aligns with international standards like IEC 61851
IEC 61851-1	Outlines fundamental specifications	Covers functional requirements and testing procedures
IEC 61851-23	Specifies requirements for DC	Focuses on DC fast charging, and procedures for interaction
IEC 61851-24	Control communication protocol	Ensures reliable communication for efficient charging
IEC 62196-3	Specifies requirements for DC	Includes Combo 1 as well as Combo 2 connectors, supports high-power DC fast charging
	Inductive Charging Standards	
SAE J1773	Specifies requirements for WPT up to 11 kW	Enhances user convenience by removing the demand for physical connectors, supports security measures and alignment guidelines
SAE J2954	Specifies requirement for WPT from 3.7 kW to 11 kW	To ensure compatibility and interoperability between different manufacturers' and systems

TABLE 7. EV coupler/connector standards [16], [19], [47], [68], [87], [88].

Code	Scope, Charging stations	Key Aspects
IEC 62196-1	Requirement for plug, socket-outlet, & coupler	Covers mechanical, and electrical performance
IEC 62196-2	Dimensional requirements for compatibility	Specifications for Type 1 and Type 2 connector
IEC 62196-3	Requirements for fast DC charging	Covers design, performance, and safety (e.g., CCS)
SAE J1772	Physical and electrical specifications for AC	Commonly known as Type 1 connector
SAE J3068	Requirements for AC and DC connectors	Covers the Type 2 and 3 (Mennekes) connectors
SAE J1772-2009	Revision of SAE J1772 with updates	Includes improvements and clarifications to connector specifications for better performance and safety
ISO 15118	Defines communication protocols	Digital connectivity for grid integration
ISO 61851-1	Defines conductive charging system	Includes connectors and couplers
UL 2594	Covers safety standards for components	Includes requirements to ensure safe operation
UL 2251	Specifies safety and performance requirements	Focuses on safety, durability, and protection
DIN 70121	Communication protocols in Germany	Communication standards for control and monitoring
GB/T 20234	Covers connectors and couplers in China	Specifications for AC and DC connectors

TABLE 8. EV communication standards [86], [89].

Code	Description	Communication Protocol	Key Aspects
ISO 15118	V2G communication	Between EV and charging station	Smart charging, and grid integration
IEC 61851-1	Conductive charging	EV charging and communications	Control and data exchange
ISO 14230	Keyword 2000	Used for diagnostics	EV diagnostics
ISO 9141	Diagnostic systems	On-board diagnostics	Protocol for physical and data link
ISO 15765	CAN diagnostics	CAN networks	Protocols for diagnostics communication
SAE J1939	Truck and bus	Heavy duty vehicle networks	Diagnostics and vehicle control
SAE J1772	EV and PHEV	AC charging	Protocols for vehicle-to-AC charger
OCP	Open charge point	EV chargers and central systems	Interoperability and remote management
GB/T 27930	National standard	Charging in China	AC and DC charging standards
DIN 70121	Control and monitoring	Charging in Germany	DC charging
IEC 62056	Meters and tariff	Smart meters and data exchange	Smart grid communication and metering

utilization and encourage wider adoption of EVs, future developments are probably going to concentrate on standardizing greater power levels, enhancing synchronization and effectiveness, and interfacing with smart grid [19], [68].

B. COUPLER/CONNECTOR STANDARDS

EVs must adhere to coupler and connection standards in order to be compatible, safe, and effective. By defining the electrical and mechanical requirements for the connections that connect EVs to charging stations, these standards provide dependable and consistent charging experiences for EVs from various geographic locations. Among the significant standards are Type 1, which is utilized extensively in North America and Japan and allows AC charging as high as 19.2kW, and Type 2 which is prevalent in Europe and can handle DC as well as AC charging up to 350kW [47]. High-power DC rapid charging is supported by the CCS, It integrates Type 1 as well as Type 2 connection functionality to improve convenience and compatibility. Another important standard that is extensively utilized in Japan is CHAdeMO, which allows for high-power DC charging. To avoid dangers like overheating and electrical malfunctions, these standards address important topics such as connection architecture, security precautions, communication protocols, and energy ratings. Applications in the real world, like the Supercharger network and Tesla's unique connector, highlight how crucial it is to follow these guidelines for quick and easy charging [87], [88]. Future developments can concentrate on delivering more power, enhancing safety features, and using smart technology to expedite the charging procedure further. Table 7 displays the summary of the EV coupler and connector standards employed by the industry.

C. COMMUNICATION STANDARDS

The interoperability and effective operation of EVs within the larger transportation ecosystem depend heavily on EV communication protocols. To ensure smooth integration and optimal performance, these standards regulate the data transmission protocols between EVs and different external organizations, including grid operators, charging stations, and other cars. Important standards include ISO 15118, which outlines the communication interface between EVs and infrastructure. This allows appropriate functionalities including plug and charge, which automates payment and authentication to improve customer convenience [89]. The IEEE 802.11p standard is also essential since it is a component of the DSRC protocol, which allows V2X transmission for enhanced safety and traffic management. A variety of EV networks are supported by the OCPP, which makes it possible for charging stations and central management systems to communicate. Implementations in the real world, like Audi's usage of V2X technology, show how beneficial these standards are for enhancing traffic flow and lowering accident rates. The integration of 5G technology to enable high-speed, low-latency communication and the addition of sophisticated cyber security measures to guard against data breaches and guarantee the reliability of systems for communication are expected to be the main areas of future development for EV communication standards [86]. Table 8 illustrates the comprehensive summary of EV Communication Standards.

VII. DISCUSSION

As EVs continue to gain popularity in the transportation sector, there are advantages and disadvantages to their integration. This discourse will put our results in the broader context of the EV ecosystem and examine how they could affect safety regulations, grid stability, the growth of the infrastructure for charging EVs, and future research initiatives. The following are the key findings and concerns:

- Development of EV Charging Infrastructure: A commensurate increase of the infrastructure for charging EVs is necessary due to their increasing spread. Our investigation classifies the level of EV charging methods at the moment, making a distinction between off-board and on-board systems, and emphasizes the necessity of infrastructure that can accommodate a range of charging needs [90]. According to this review, fast-charging stations are essential for shortening charging periods and enhancing consumer convenience, but they also put a heavy load on the grid. Research into more effective and grid-friendly charging options, like usage of renewable power sources, is therefore becoming more and more crucial. In order to avoid overloading certain grid segments and to guarantee fair access to charging stations in rural as well as urban regions, the geographic placement of charging stations must also be meticulously planned. To support effective infrastructure planning, Table 9 summarizes the key parameters that must be considered when designing an EV charging system. These parameters—ranging from power and safety requirements to grid impact and user interface—are critical to ensuring reliable, scalable, and user-centric deployment of charging solutions. Understanding and controlling these factors is essential for developing a resilient and future-ready EV charging infrastructure.
- EV Safety Standards and Regulations: Safety is the foremost concern in the design and implementation of EV charging stations [91], [92], [93]. The study outlines a number of worldwide safety guidelines and regulations that regulate EV charging, but it also points out weaknesses that must be fixed to guarantee these systems operate safely. New safety challenges arise with the evolution of technology, especially with regard to high-power lightning-fast charging and the incorporation of V2G systems. The development of sophisticated diagnostic instruments for early defect detection, better thermal control mechanisms, and strong cybersecurity protocols to guard against potential attacks are just a few of the safety measures that will need to be improved in the future [94].
- Grid Stability and Integration Challenges: The effect of widespread EV integration on grid stability is one of the most significant concerns raised [95]. Due to EV charging, there is a rise in power demand, which puts the system at danger of voltage fluctuations, higher load, and even outages. According to our analysis, innovative control techniques like smart charging and, V2G solutions are essential for reducing these hazards. By adjusting charging schedules in response to grid conditions, these techniques can lower peak demand and improve grid resilience. However, such technologies necessitate collaboration amongst stakeholders, particularly grid operators, legislators, and EV manufacturers.
- Hydrogen Vehicles: The automotive industry is undergoing a notable transition as electric and hydrogen cars become the front-runners in the competition for environmentally friendly mobility. This shift presents a difficult

TABLE 9. Key parameters for designing an EV charging system. Importance levels: ★ - Low, ★★ - Medium, ★★★ - high [14], [20], [34], [41], [86], [90], [95].

Category	Parameters	Importance	Design Impact	Control Strategy
Power Requirements	Charging Power, Voltage Level, Current Rating	★★★	Performance, Compatibility	Power electronics, transformer design, current sensors
Charging Mode	AC/DC, Conductive/Inductive, Level 1/2/3, Mode 1–4	★★★	Infrastructure, Efficiency	Charging topology selection, system architecture
Battery Compatibility	Battery Type, Capacity, SoC	★★★	Battery Safety, Efficiency	BMS integration, charge control algorithms
Communication Protocols	ISO 15118, OCPP, IEC 61851, CAN	★★	Interoperability, Control	Communication modules, firmware
Safety Measures	Grounding, Overcurrent, Thermal Monitoring, Isolation	★★★	Safety, Regulation	Fuses, circuit breakers, temperature and voltage sensors
Grid Impact	Load Management, V2G, Power Factor, Demand Response	★★	Grid Stability	Smart charging, dynamic scheduling
Connector Type	CCS, CHAdeMO, Type-1/2, Tesla NACS	★★	Compatibility	Hardware selection, adapter support
Environmental Factors	Temperature, IP Rating, Humidity	★★	Reliability	Enclosure design, derating factors
User Interface	Display, Payment Options, Authentication	★	Usability, Adoption	HMI design, mobile app integration
Installation Site	Urban/Rural, Residential/Commercial	★★	Cost, Permitting	Site survey, modular layout, compliance planning

task because each technology has its own set of benefits and drawbacks. Battery-powered EVs have become more popular because of their increased efficiency, less emissions, and expanding infrastructure for charging. They are hampered, nevertheless, by their short range, lengthy intervals for charging, and the environmental effects of battery manufacturing and disposal. However, due to the high cost of producing hydrogen, the scarcity of refuelling places, and the requirement for additional infrastructure, hydrogen vehicles fail to live up to their promises of quicker refilling and longer ranges. The battle between electric and hydrogen-powered cars will determine the future direction of the automotive industry, impacting customer acceptance, technological advancement, and international environmental objectives as manufacturers and legislators work through these obstacles.

A. FUTURE RESEARCH DIRECTIONS

The synthesis of the literature identifies several crucial areas that require more investigation, as discussed below:

- Infrastructure and Grid Integration: More thorough research is a vital need to determine how EV charging affects grid infrastructure over the long run, especially in situations where EV penetration is significant. Most specifically, smart grid integration, real-time load balancing, and the strategic placement of charging stations to support both urban and rural adoption.
- Technological Advancements: Further research is essential to develop more economical and efficient EV charging technologies. This contains advancements in bi-directional charging (V2G), solid-state batteries, and high-power fast charging solutions that uphold battery health and safety.
- Sustainability and Renewable Energy Integration: To build more environmentally sustainable energy ecosystems. The extensive research should explore the integration of renewable sources such as solar and wind into EV charging infrastructures. That can be supported by scalable battery management systems (BMS) for reliable energy supply.
- Interdisciplinary Collaboration and Policy Research: The complexity of EV integration calls for interdisciplinary collaboration among experts in computer science, electrical engineering, materials science, and policy. Such efforts are essential to develop holistic solutions that address technical, economic, and regulatory challenges, ensuring widespread societal and industrial benefits.

VIII. CONCLUSION

With a focus on advancements from 2020 to 2025, this review has offered a thorough overview of the state of EV charging methods, coupler technologies, energy sources, and charging standards that shape the current EV ecosystem. By synthesizing insights from 81 pivotal studies, the paper offers a cohesive and up-to-date perspective on the evolving EV charging landscape, making it a valuable reference for both researchers and industry stakeholders. The paper also suggests a number of directions for future study, stressing the significance of creating charging methods that are more sustainable and efficient, investigating the incorporation of energy sources that are renewable, and encouraging interdisciplinary cooperation. To fully achieve EVs' potential as an essential component of the global power revolution, these difficulties must be addressed. By offering a structured and comprehensive synthesis of recent advancements, this paper serves as a practical roadmap for developing efficient, scalable, and sustainable EV charging solutions. In summary, even though EV charging methods have come a long way, more research and development are still needed to get beyond the remaining challenges. By achieving this, the EV sector will be better positioned to support the worldwide transition to more environmentally friendly and sustainable modes of transportation, which will ultimately help achieve more ambitious energy and environmental goals.

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