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ELECTRIC VEHICLES CHARGING STATIONS AND THEIR INFLUENCE ON THE ELECTRICITY UTILITY GRID

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Abstract

The adoption of electric vehicles (EVs) has emerged as a significant measure to reduce greenhouse gas emissions and promote cleaner transportation towards the goal of decreasing temperature increase over 0.5°C by 2050. The evolution of battery technology allows for massive exploitation of EVs as they require low maintenance and have over 200% higher efficiency in total than conventional vehicles. However, the need for rapid implementation of charging stations poses unique challenges for electrical distribution networks. This paper investigates the influence of electric vehicle (EV) charging stations on the electricity utility grid, focusing on their technological frameworks. The capabilities and challenges of lithium-ion battery technologies are examined, including their high energy density and reliability, while addressing concerns over performance limitations due to aging cause by high temperatures. The work outlines current charging technologies, classifying them into AC and DC wired systems, wireless charging methods, and battery exchange systems. Rapid advancements have reduced charging times to 10–15 minutes for 80% capacity using high-voltage systems. Furthermore, the integration of Vehicle-to-Grid (V2G) systems, where the EV as an separate energy storage system exchanges power with the utility grid, was found to reduce peak load by over 4% and improve energy efficiency, lowering energy costs by 40% and scheduling costs by 14%. V2G technology enables real-time bidirectional energy transfer, supporting grid stability and sustainability. Challenges such as communication reliability,

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data privacy, and battery degradation due to increased charging cycles were discussed. The study concludes that the adoption of EVs and their integration with utility grids through V2G systems presents a promising approach to enhance sustainability, although overcoming technical challenges and optimizing battery life are crucial for widespread implementation. The findings emphasize the pivotal role of aggregators in managing power exchanges, predicting load fluctuations, and ensuring a reliable energy supply.

Keywords: EV; stations; grid; vehicle; battery

1. Introduction

Climate change and the need for greener electricity have been the main focus of research towards an eco-friendly means of energy production [1]. Transportation plays a key factor in power consumption, especially road, ship, railway, and aviation which accounts for 55% of the overall energy consumed [2]. In addition, 30% of total greenhouse gas emissions come from the automotive industry as modern vehicles utilize an internal combustion engine for their operation [3, 4]. During fuel combustion, the engine produces gases such as CO_2, NO_2, NO_X, and CO enhancing the greenhouse effect while causing serious health issues [5]. Research conducted before and after the announcement of a 21-day lockdown in India revealed a decrease in air pollution indexes and a significant improvement in air quality [6].

The climate and energy policies place a high priority on safeguarding air purity and undertaking measures to minimize air pollution due to transportation [7, 8]. The emissions of substances such as CO_2, CO, and NO_X, equally by the transport sector have increased over the last 30 years in 1990 [9]. The combination of technological advancement resulted in the introduction of modern vehicles like Electric (EV) or Hybrid Electric vehicles (HEV) [10, 11]. The electric vehicle is considered the future of transportation due to its plethora of benefits like zero emissions, less maintenance, and higher efficiency [12]. Their operation is based on the electric motor which is powered by lithium batteries. Compared to conventional vehicles, energy waste can be reduced by over 300% as shown in Table 1 below [13].

Tab. 1. A comparative approach to the impact of different vehicle types on road usage [13]

Technology	Energy Loss	Efficiency	Energy used (kWh/km)
Petrol	86%	14%	1.36
Diesel	80%	20%	0.95
LPG	84%	16%	1.19
CNG	81%	19%	1.00
PHEV	55%	45%	0.42
FCV	78%	22%	0.87
Battery/EV	33%	67%	0.28

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Furthermore, electric vehicles are much more advantageous technologically, since they don't require a gearbox, and have full torque at low speeds [14]. In recent years, the automotive industry has rapidly increased electric vehicles production as part of the incentives by the authorities for their purchase. However, a smooth transition to electric mobility requires proper utilization of renewables and manufacturing new charging stations with respect to the impact on the utility grid depicted in Figure 1 [15].

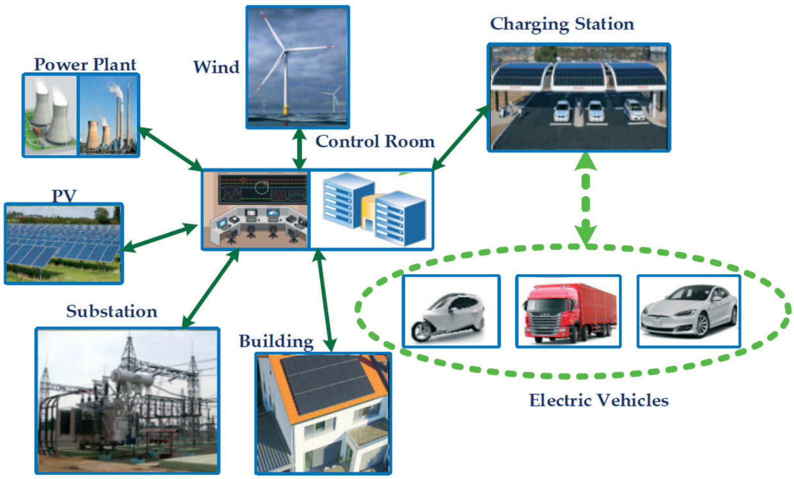

Fig. 1. A Charging station connected to the microgrid [15]

EV charging stations are powered by the utility grid, thereby causing extensive strain while increasing the load demand [16]. However, electric vehicles could serve as a link between the grid and renewable energy sources, as energy storage units via the Vehicle to Grid system. Thus, EVs can contribute to reducing peak demand plus the environmental footprint, while enhancing the reliability of the grid.

The aim of this paper is to review the impact of the electric vehicle charging stations on the electricity distribution network. As electric vehicles market is growing rapidly as they inherit a plethora of benefits, the need for more charging points and energy demand are increasing. This work summarizes the technologies of lithium batteries and electric chargers currently available and their impact on the utility grid along with Vehicle to Grid and Grid to Vehicle systems, to enhance sustainability. Therefore charging cost will be low ensuring the grid sufficiency to meet the energy demand as well as operate more reliably, while stress is reduced due to avoidance of peak loads.

The manuscript is structured into four main sections. Chapter two describes the different types of pure and hybrid electric vehicles along with an introduction in lithium batteries and

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their operation. In the third section, charging technologies and their prospects are summarized. Next section is about the utility grid and the impact of electric vehicles on its operation including the utilization of V2G system for power exchange. Then the discussion section summarizes the findings of this study. In the last section, conclusions about the the impact of electric vehicles and V2G system for minimizing stress on the grid and ensuring power quality and sufficiency are stated.

2. Electric Vehicles and Lithium Batteries

2.1. Evolution of Electric Vehicles

In the 1920, electric vehicles accounted for only 28% of the total car market produced in the United States. However, due to the high cost of producing electric vehicles along with the rapid advancement of internal combustion engine (ICE) car technology, promotion of electric vehicles was significantly slowed down. At the beginning of the 21st century, high levels of environmental pollution and concerns about the depletion of fossil fuels brought to the surface the development and improvement of electric vehicles with a view to their full adoption by the market and the buying public [17].

Throughout the years, the increasing number of conventional vehicles has largely contributed to increased greenhouse gases, impacting the energy crisis as well [17]. Thus, research has evaluated the environmental repercussions of energy vehicles on the planet [18]. Several countries have invested in EVs as an alternative solution to ICEs due to the benefits they introduce [19, 20]. More specifically, China, as the world's biggest vehicle industry, is committed to promoting electric vehicles to reduce fossil fuel usage, while Europe aims to decrease temperature rise by 0.5°C by 2050 [20]. The cooperation between car manufacturers and respective governments has contributed to the improvement of electric vehicle infrastructure technology. The existing electric vehicle technology is now divided into the following main categories [18–20]:

- <u>Hybrid Electric Vehicles</u> (HEVs): Vehicles that combine an electric motor and a traditional internal combustion engine are known as hybrid electric vehicles or HEVs [21]. The battery is charged by the energy produced by the ICE or regenerative braking and supplies the electric motor with energy to propulse the car at low speeds.
- <u>Plug-In Hybrid Electric Vehicles</u> (PHEVs): Both an electric motor and an internal combustion engine are components of plug-in hybrid electric vehicles. The battery capacity is increased to be charged by the grid, so the PHEV can operate as pure electric for a shorter range or as a pure hybrid where the battery is dropped below a certain point, resulting in lower exhaust emissions and fuel consumption [22].
- <u>Fuel Cell EVs</u> (FCEVs): Fuel cells are electrochemical devices that generate electricity as a chemical reaction triggered by the ingestion of fuel and air in the presence of the

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electrolyte resulting in electricity generation. Fuel cell electric vehicles are eco-friendly, as only water and heat are generated. They introduce higher efficiency with relatively quiet operation due to the minimal number of moving parts however, its implementation is currently very expensive in the automotive industry [23].
- Battery Electric Vehicles (BEVs): These vehicles use an electric motor powered by lithium batteries with increased regenerative capabilities. The major advantage of electric vehicles is the lower mechanical drivetrain, which makes the vehicle lighter, with no emissions. However limited range, high charging time, and battery limitations due to premature aging caused by increased temperature are still important issues to be faced [24].

Among these, a pure electric vehicle is regarded as the most efficient way to achieve environmental solutions [25]. Their operation relies on lithium batteries to supply the electric motor as the propulsion system. The main components of a pure electric vehicle are displayed in Figure 2 [26, 27]:
- motor: the electric motor is the part of the propulsion system with a single or multi-speed transmission,
- battery: the accumulator is charged by the grid to power the motor and auxiliary loads,
- controller: the DC-AC converter monitors the power demand and regulates the energy flow to ensure smooth powering of the electric motor.

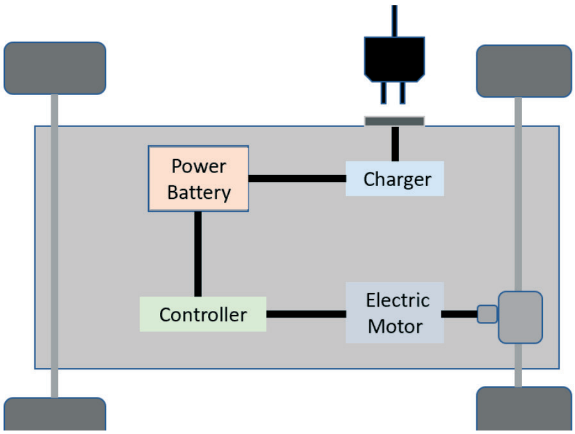

Fig. 2. A simple design of a Pure Electric Vehicle [17]

Safety is a crucial aspect of electric vehicle battery design, as battery failure can be severe [28]. Therefore, car manufacturers have invested heavily in the safety of EV operation and charging, applying appropriate safety measures such as current interrupt devices, fuses, vents, and a main control unit [29]. This Management system (BMS), constantly monitors cell voltage and temperature and cooling systems [30, 31]. That is why batteries are part of the chassis, preventing a possible deformation if an accident occurs.

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As charging time is still an important drawback and has to be addressed, recent improvements in the charging capability of electric vehicles have significantly reduced charging duration to 80% capacity within 10 minutes to 15 minutes [32, 33]. Cell chemistry and material limitations are the primary obstacles to EV battery adoption. During charging, lithium ions move from the cathode to the anode. The rate of this movement is controlled by the ion intercalation of lithium and the diffusion rate. If the charging rate is swift, lithium plating occurs on the anode surface, leading to increased temperature thereby affecting its capacity, lifespan, and safety [34, 35]. There have been various attempts to increase the charging rate, such as preheating cells to improve electrode dynamics and using high-voltage systems to reduce current levels. An advanced BMS is required to monitor and optimize operations based on these parameters [36, 37].

Power capability is an additional critical factor in the performance of electric vehicles. The quantity of power required is contingent upon the type of vehicle [38]. Upgrading battery capacity leads to waste energy and higher costs so a balance between various aspects of performance is imminent [39, 40]. To enhance battery performance, the battery cells in electric vehicles are fully constrained. This means that they are not only compressed into modules to reduce swelling, but they are also connected to the cooling plate to improve cooling efficiency so if maintenance is required for a cell or the plate, it becomes cost-inefficient [41].

2.2. Battery Technology

The introduction of electric vehicles presents optimal ways of protecting the environment and saving energy, which makes them an effective solution to avoid fossil fuel depletion and greenhouse gas emissions [42]. The I.E.A (International Energy Agency) revealed the results of the simulation "EV30@30model", assuming that there will be 240 million electric cars around the world by 2030 [43]. Electric cars are a promising transportation tool since they are energy-efficient, clean, noiseless, and require little maintenance only at specific parts , including the battery cooling system, suspension and brakes [44]. Despite these benefits, there are limitations to electric vehicle battery technology regarding weight, capacity, lifespan, and high battery cost that remain major obstacles to the widespread acceptance of electric vehicles [45]. Nonetheless, numerous industries and organizations are daily investing in the advancement of battery technology, for example, the USA spent $2 billion on battery technology development [46].

Batteries provide the vehicle with power to cover the electric motor and auxiliary loads, as well as charge the 12 V battery via a DC-DC converter [47]. It also functions as a voltage stabilizer, reducing any sudden surges in the charging system and thereby safeguarding various electronic components. The main battery technologies currently being used for energy storage in electric vehicles are presented below [48, 49]:

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- Lithium-Ion (Li-Ion): The dominant battery technology applied to electric vehicles. They are preferred in electric vehicles since they have high energy density and exhibit increased power per unit mass. They are reliable, require minimal upkeep, and have a prolonged lifespan. The disadvantages of this type of battery mainly have to do with high developing temperatures, which affect performance, aging, and safety.
- Nickel-Metal Hydride (Ni-MH): This type of battery is an alternative technology, primarily utilized in hybrid electric vehicles. The advantages of Ni-MH batteries are their lifetime, capacity, and efficient operation in a wide range of temperatures. Some of their disadvantages are the increased weight, cost, and decreased energy density, compared to lithium batteries, hence they do not apply to modern EVs.
- Lead Acid: They were the predominant energy storage technology in electric vehicles until the early 21st century, mainly because of their lower cost and availability. The increased weight, limited capacity as well as lower efficiency in large discharges and extreme weather conditions make it difficult for electric vehicles to adopt them.
- Lithium-Polymer (Li-Polymer): Lithium polymer is a Li-Ion technology. The anodes comprise carbon and metal oxides and lithium is inserted between them. Lithium is in ionic form, as it is intercalated with carbon anodes. This makes it less reactive than in its pure form. The primary advantage of these batteries lies in their design, which is based on the utilization of a solid-state electrolyte, making them less hazardous in the event of an accident. All these technologies are presented in Figure 3 [48].

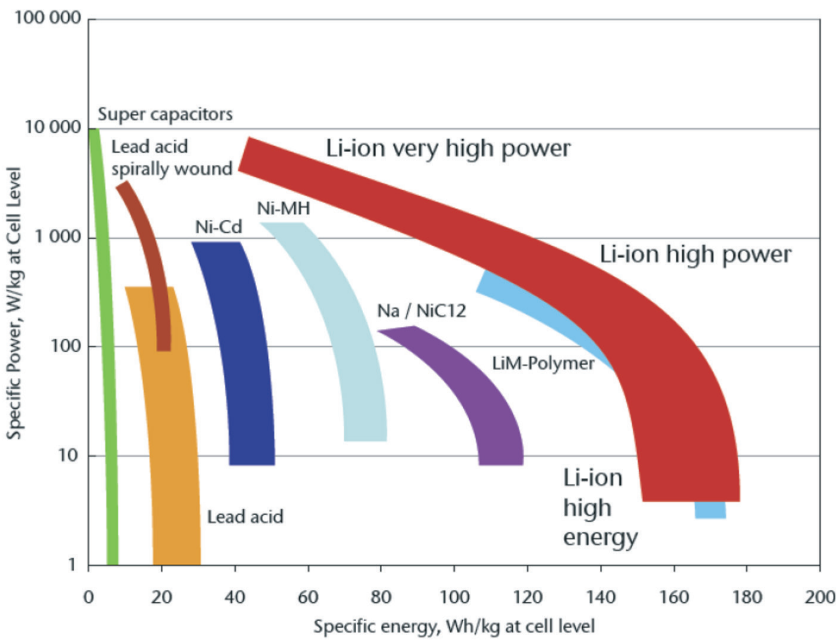

Fig. 3. Specific power and energy of different battery types [48]

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The two main battery technologies utilized in electric vehicles as summarized in Table 2, are Ni-MH and Li-ion. Currently, most electric vehicles use Li-Ion batteries since they are more advanced while Ni-MH can still be found in hybrids or plug-ins [50, 51].

Tab. 2. Batteries for electric vehicles that are used by selected vehicle manufacturers [50]

Company	Country	Vehicle model	Battery technology
GM	USA	Chevy-Volt	Li-ion
		Saturn Vue Hybrid	NiMH
Ford	USA	Escape, Fusion, MKZ HEY	NiMH
		Escape PHEV	Li-ion
Toyota	Japan	Prius, Lexus	NiMH
Honda	Japan	Civic, Insight	NiMH
Hyundai	South Korea	Sonata	Lithium polymer
Chrysler	USA	Chrysler 200C	EV Li-ion
BMW	Germany	X6	NiMH
		Mini E (2012)	Li-ion
BYD	China	E6	Li-ion
Daimler Benz	Germany	ML450, S400	NiMH
		Smart EV (2010)	Li-ion
Mitsubishi	Japan	iMiEV (2010)	Li-ion
Nissan	Japan	Altima	NiMH
		Leaf EV (2010)	Li-ion
Tesla	USA	Roadster (2009)	Li-ion
Think	Norway	Think EV	Li-ion, Sodium/Metal Chloride

3. EV Charging Technologies

3.1. Stations for Charging EVs

The commercial success of electric vehicles is highly dependable on the infrastructure of easily accessible charging stations, which are straightforward to use and with low energy costs. Due to the absence of this condition, a significant number of potential purchasers may be hesitant to procure one, despite its superior performance [52]. For electric mobility to thrive, charging requirements must be met in every circumstance, so to make electric vehicles more widely available, the charging system needs to have capillary diffusion. If a sufficient number of individuals start using electric cars, sufficient charging facilities must be available [53, 54]. The widespread availability of electric vehicle charging infrastructures helps reduce drivers anxiety regarding the EV range. Figure 4 reveals the number of slow and fast chargers in distinct continents in 2023 [53].

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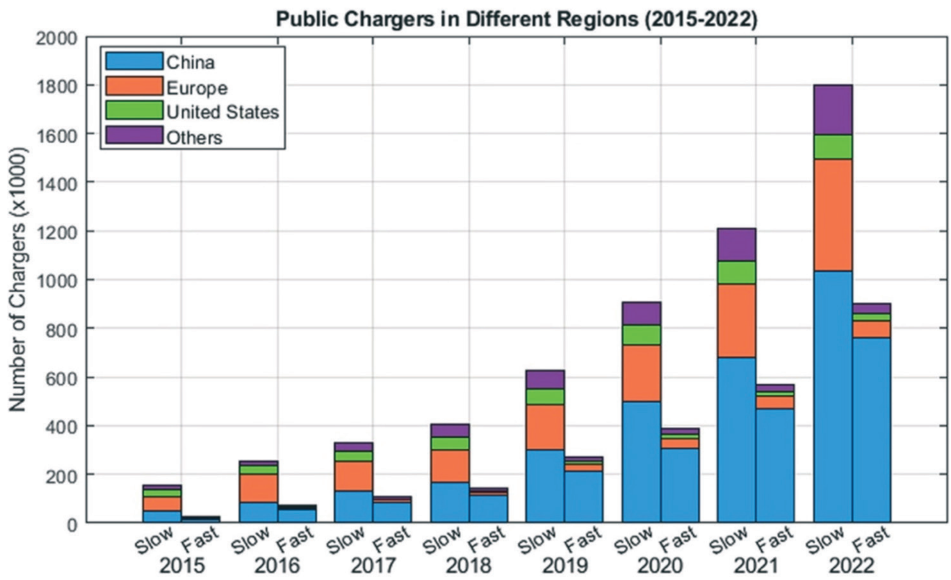

Fig. 4. Evolution of available charging stations from 2015 to 2022 [53]

The availability of electric vehicle charging stations is primarily divided into private and public access. Private access is mainly residential or private businesses that use domestic supply for charging. Charging locations are divided into 4 Groups [55, 56]:

- School Education,
- Workplace,
- Shopping Center,
- Public parking lots.

Figure 5 depicts that the starting time for charging is determined by location. The finding indicates that there is a peak in demand at the time students or staff arrive at school followed by another peak after lunch. There are plenty of people going downtown for lunch in the public parking lot at 1 p.m. An unanticipated peak occurs at 10 a.m. in the retail sector. It is hypothesized that this peak occurs during the opening of the shopping center [56]. It can be anticipated that the impact on the utility grid will be substantial, even during peak hours to ensure grid stability.

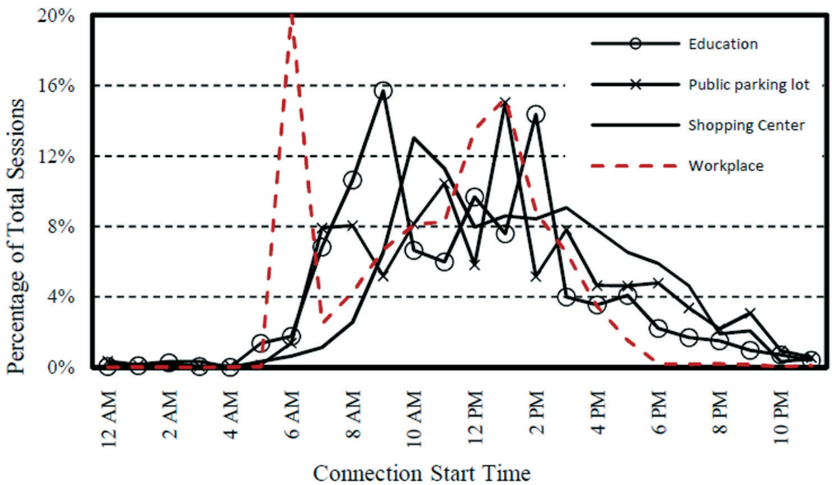

Fig. 5. The total percentage of use of different charging facilities during daily life [55]

3.2. Charging Methods

Depending on charger connectivity, charging methods are divided into three categories: wired (conductive), wireless charging, and battery exchange. All three EV charging methodologies are shown in Figure 6 [57].

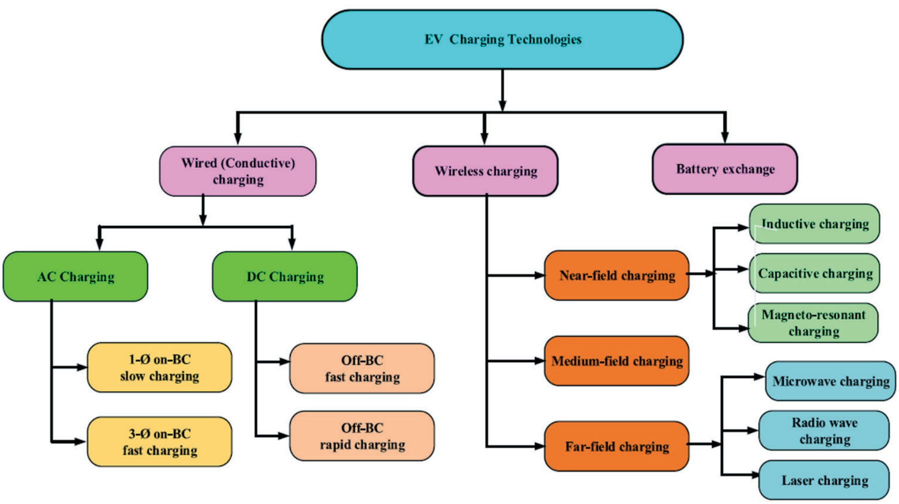

Fig. 6. Electric Vehicle Charging Technologies [57]

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A. Wired (Conductive) Charging

Depending on the input voltage the wired-based technologies are divided into two categories of charging systems: AC and DC charging. EV receives power from the grid through the AC charging system and the onboard battery charger converts it to DC to charge the battery, hence the benefit of the AC charging system is that it eliminates the need for a charging station [55, 56]. In contrast, the DC charging system converts the AC grid voltage to DC by charging the electric vehicle battery directly from the off-board charger rather than the integrated module. Additionally, the wire charging system provides a vehicle-to-grid (V2G) adaptivity as the vehicle can operate both as a load and a supply. The above types (AC and DC charging systems) are subdivided into two groups: 1Ph on-board slow charging and 3Ph on-board fast charging, for AC charging and off-board fast – rapid charging for DC shown in Figure 7 [57, 58].

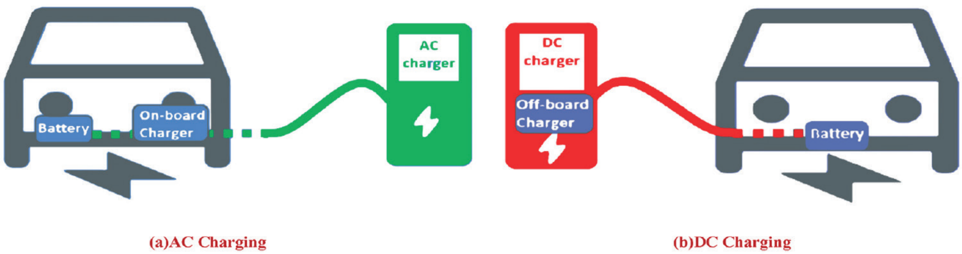

Fig. 7. Wired Charging Technology: AC and DC charging [56]

Three Phase supply offers a faster charging capacity due to its power rating of up to 20 kW. Dual-active bridges are the most common configuration for these charging systems. This approach is primarily favored for electric vehicles because of its ease of use. For DC, the supply is capable of supplying electrical vehicle power without the necessity for any extra wiring. Therefore, the overall weight and mass of the driving system have significantly decreased [57]. Large automakers like Tesla and Hyundai, have created DC chargers that can fill the batteries in an hour. This layout power range is between 20 kW and 120 kW while voltage can range from 320 volts to 450 volts. In off-BC rapid charging, voltage ranges from 320 V to 500 V with the ability to charge within 15 minutes [58].

B. Wireless Charging

In the charging station or a road, an induction coil generates alternating current, hence the formation of the magnetic field which rotates, causing the induced current via the coil of the portable device to oscillate [59]. This process results in the conversion of alternating current to direct current, which is used to charge the battery. The rotating magnetic field generated by the transmitter coil generates AC power output at the receiver coil. The stability of the resonance frequency is imminent to ensure the effectiveness of wireless charging. Addition-

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ally, to maintain consistent resonant frequencies, compensating networks are used at both ends of the transmitter and receiver coils. The battery management system at the receiver converts AC into DC delivering it to the batteryas shown in Figure 8.

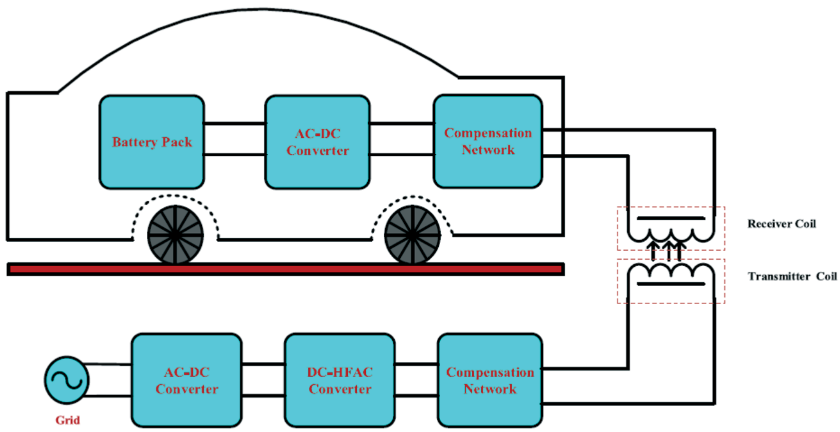

Fig. 8. A simple structure design of a wireless station for charging [56]

C. Near-Field Charging

There are 3 types of near-field charging systems [60, 61]:

1. Inductive charging: A highly effective and affordable charging alternative for modern vehicles is inductive charging, which involves the transfer of power from a transmitter to the receiver plate through an electromagnetic field. Designing a suitable power pad is essential to increase reliability and efficiency. However, there are still several challenges facing wireless power transfer systems, including the design of power pads and coils and the protection against electromagnetic fields.
2. Capacitive charging: Applying an electric field through the two plates, the transmitter and receiver, are connected in parallel, operating as two distinct capacitors, to produce an electric field. Thus the induced current is powering the pad, connected directly to the load or the power source. The rate at which the electric field changes between the transmitter and receiver pads is equal to electromotive force.
3. Magneto-resonant charging: Because of the resonant frequency, magneto-resonant charging, has a higher efficiency than inductive charging. By adding compensating capacitors, the frequency can be increased, offering the ability for high-distance transmission. There are 4 different phases for these methodologies to be deployed [59, 60]:

- phases 1 and 2 of the deployment of these charging technologies are for basic residential systems and parking spaces respectively,
- phase 3 accounts for on-street parking,
- lastly fourth phase can be applied to dynamic systems.

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D. Medium-Field Charging

This charging technology is based on the mechanical force developed by interacting two synchronized permanent magnets as the main energy-carrying medium. Medium-field charging is suitable for charging between 1.5 kW and 3 kW. It is also capable of transmitting 3 kW for small ranges [58]. Furthermore, it is noteworthy to mention that as of late 2009, research demonstrated charging prototypes equipped with magnetic gears that were capable of delivering 1.6 kW at a 5 cm interval with an efficiency of 81% [60].

E. Far-Field Charging

Technologies that employ electromagnetic radiation to charge across high distances include radio waves, microwaves, and laser charging. They are divided into 3 categories [58–60]:

1. <u>Microwave charging</u>: Evaluations of microwave charging systems have been carried out in situations where a long-distance power source is necessary, such as helicopters, experimental planes vehicles, etc. Long-distance charging has the drawback that if communication between the 2 pads is lost, charging immediately shuts down.
2. <u>Radio wave charging</u>: The fundamental principle behind radio wave charging is the propagation of electromagnetic fields. For this kind of charging technology, a rectenna with a high-frequency filter can absorb the transferred power. The rectifier ensures that the battery is charged sufficiently, with the appropriate DC voltage and charging current. However, the efficiency of this module is very low, necessitating further research to reach the required power efficiency for charging electric vehicles.
3. <u>Laser charging</u>: An ultra-high frequency beam, up to 3.6 THz is utilized in this technology in order to transmit the energy required. It is produced by the allocated laser transmitter, picked up by a distributed laser charging receiver. Subsequently, the beam is directed towards a DC/DC power converter, which regulates the output to be appropriate for battery charging.

F. Battery Exchange

Batteries exchange systems are based on the ability of owners to rent and replace batteries every month. Battery swapping is a common technique used in electric forklifts. To receive power, an electric vehicle must be parked at a designated charging spot. Then the battery is removed and stored, while a new fully charged battery is installed in the vehicle, as a more convenient and simple strategy. The limitations of battery-swapping technology include building infrastructures for charging and swapping stations, as well as significant capital expenditures for such stations [61, 62]. A diagram for this scheme is displayed below in Figure 9.

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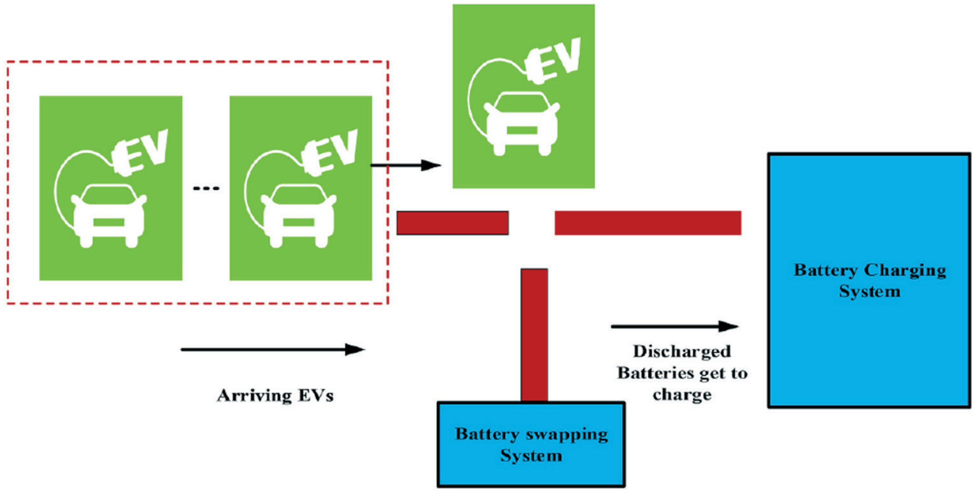

Fig. 9. Simple diagram of a battery swapping system [56]

4. Electricity Distribution Network

The escalating demand for energy and the gradual transition to electricity as an environmentally friendly energy source underlines the importance of the electricity distribution network. Grid operation is made up of three main systems: electricity generation system, transmission system, and distribution system [63]. The generated electricity from the power stations is increased by using step-up voltage transformers for more economical long-distance transmission. The transmission system is responsible for transferring the power to the distribution centers. The power transferred is either at extra-high voltage (EHV) or high voltage (HV). The distribution system then converts the HV to the medium voltage level (MV) in the suitably configured power substations. The power is then transferred via medium-voltage lines to urban centers, where it is reduced to low-voltage (LV) to reach the consumers [64].

The structure of the electricity distribution network comprises several electrical components that contribute to the transmission of electricity to consumers. This equipment pertains to transmission lines, substations, step-down and step-up voltage transformers, insulators, lightning arresters, and isolation switches, which are represented in Figure 10.

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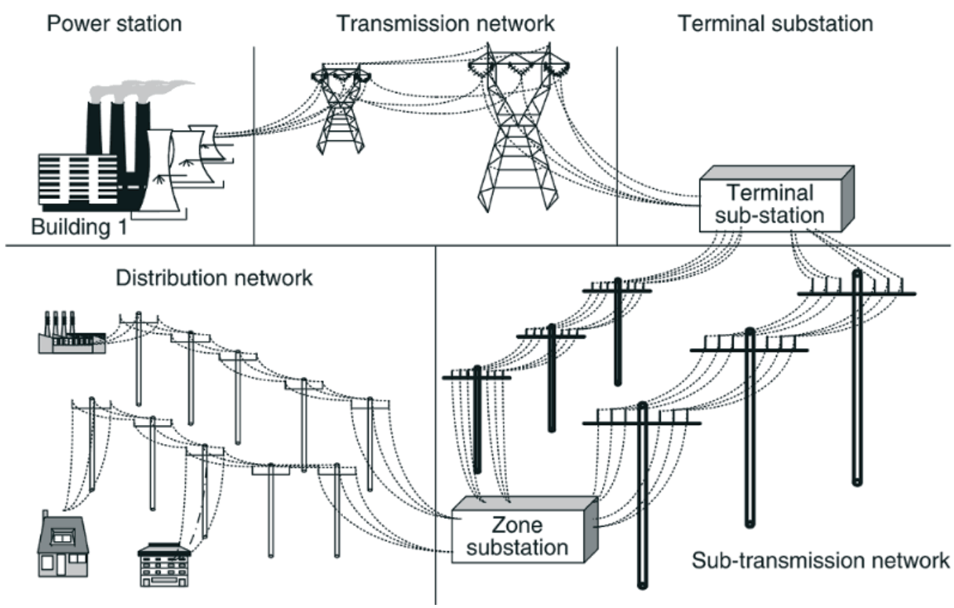

Fig. 10. Representation of the Electricity Supply System [63]

As the automotive industry expands and invests in electric vehicles, power transactions between EVs and the grid will become increasingly frequent [65]. A Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) electricity concept with power exchange between the two layouts offers the ability for electricity trades to ensure power competency for the grid. During peak load periods, electric vehicles provide the grid with additional energy, and when in time of excess energy, the EV batteries are charged slowly for protection [44]. Hence energy waste is limited and power quality is enhanced [66]. A power connection to the electrical grid, communication that controls charging and discharging, and a way to audit the services provided to the grid are the three essential parts of a V2G system depicted in Figure 11 below [67].

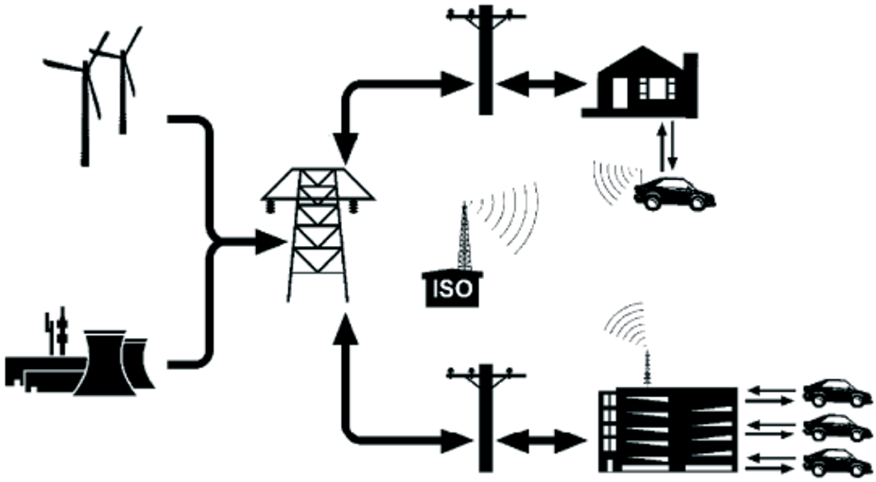

Fig. 11. The establishment of power lines and wireless control connections between automobiles and the grid [66]

The widespread integration of electric vehicles in recent years, is bringing certain challenges that have to be addressed. As EV charging is related to people living patterns, a certain regularity is noticed as users mainly charge during the night hours or midday [65]. Therefore the load on the grid is increased rapidly, which at peak hours adds additional stress to components like the transformer, cables and fuses. This issue can be migrated by certain intensives like reduced energy cost when renewables production is peaked to switch the charging period to morning hours, e.g. 10 a.m. to 3 p.m.

A study in the United States shown that EVs are parked 95% of the time, so a significant resource for the grid is available at peak hours for example Air Conditioning utilization at summer. This power would be typically produced by sources that are expensive like hydropower systems, hence the idle EVs will provide cleaner and cheaper energy to cover the demand, so cost will be decreased. In addition the V2G scheme is more efficient, as the vehicles are ready to provide power immediately even at a lower discharge rate, to protect the battery, via the bidirectional converter [66, 67].

Electric vehicles must have three key components to adopt a V2G concept: a special charger, power bi-directionality, and communication capacity [66]. Although the charger output capacity is crucial to economy and efficiency, vehicle-to-grid systems have the potential to operate at varying power levels. The supply equipment of an electric vehicle is generally divided into three levels [68–70]:

- <u>Level 1</u>: Uses the lowest power outlets that are available, which leads to low power capacities (1–2 kW).
- <u>Level 2</u>: Adopts increased capacity range with up to 20 kW capacity.

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- Level 3: Over 50 kW as power output is provided by using DC off-board battery chargers. This level is commonly known as quick or fast chargers.

The majority of V2G projects are expected to use Level 2 chargers for the next few years, despite the fact all three charger options would be appropriate for V2G. This is because Level 2 chargers offer the best balance for power sufficiency and reduced cost for the typical user who charges their EV in residential areas [70, 71]. Once the EV has ensured grid connection, the next step is the need for a bidirectional converter and sufficient communication. The process of V2G demand on the EV supply equipment must be the 2 standards stated above to direct power flows and provide messages to the power grid operator [72].

The next aspect of a V2G system is the aggregator or the control unit. For the V2G system to function, an aggregator is not necessary in a technical aspect. Instead, an individual electric vehicle is possible to communicate directly to the utility grid operator [73]. It remains a priority that the number of EVs connected to the grid and supply power must be coordinated and estimated by the aggregator to ensure stability and flexibility as well as predict power fluctuations and sufficiency, beyond the technical and market-required grouping capacity [66].

Moreover, an aggregator has the potential to acquire knowledge from previous EV charging behaviors to predict the optimal utilization of V2G resources [74, 75]. When power from renewables exceeds demand during the day, EVs can be charged with the level 2 module to enhance lifespan and grid stability. In conclusion, aggregators are the key link for this layout, since they are responsible for power exchange and grid monitoring coordination. Figure 12 shows the V2G process summarized for EV owners, aggregators and the power grid, as a business scheme [65,70].

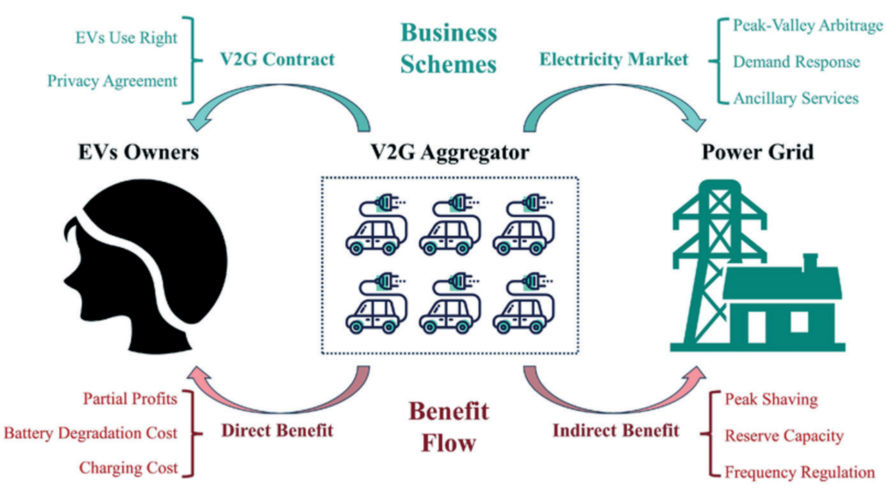

Fig. 12. Vehicle to Grid feasibility Scheme [65]

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The concept of time-of-use (TOU) tariff can be applied, guiding people to use electricity when they really need it [65]. For example in China, the country with the largest fleet of EVs and electric buses, the peak tariff accounts for 0.16 $/kWh, while the valley tariff is 0.04 $ per kWh, exactly ¼ of the price which can be fed in the EV owners directly or via a discount during charging in the evening. In the same time, an intensive should available, so the mean electricity price for all users may be decreased to 12 cents per kWh, thus a drop of 4 cents and the rest goes as aggregation to the EV owners. Studies show that a typical 60 kWh to 80 kWh batteries are ideal leading to a shift of over 4% of peak load to valley arbitrage with huge profit space [65, 76].

5. Discussion

With the adoption of V2G, the spot market layout, thus real-time power exchange when required is available.This market is expected to grow, reaching 52 million dollars by 2030 with a 28% increasing annual rate [65]. As the number of EVs available to the aggregator are increased, the profits, both for economic and feasibility, like peak shaving operation are multiplied. Results show that the energy and environmental costs can be decreased by over 40% while the EV scheduling cost dropped by 14%, allowing the EV users to gain extra credits with minimum stress on the utility grid.

Thus, the role of the aggregator is essential, as the electricity demand and cost, availability of EVs to provide power have to monitored in real-time to ensure power quality, voltage and frequency regulation along with maximum EV contribution efficiency. Lastly load forcasting is also essential to avoid risky situations like extensive peaks which can even lead to power outages. Even in a situation like this, the EV batteries can operate as black start power sources to provide energy to core services like hospitals and substations DC systems for monitoring of the various components [70–72].

For the implementation of any new technology, challenges are inevitable. V2G faces certain complexities in the following areas: Communication and battery degradation [65]. As the adoption of this scheme required massive packs of data for centralized optimization and configurations, challenges to communications stability are evident. Delay must be minimum, with ensured real-time transmission, hence additional infrastructure is required. Data privacy is a necessity so information must be encrypted to avoid data leakage and tracking, so a new communication protocol, formulated as ISO 15118-1:2019 is applied as the main interface.

Another technical difficulty is related to battery degradation. Increased battery cycles and rapid charging/discharging will lead to premature aging. Literature is focused on this area, with studies inquiring that V2G as a service may not outweigh the battery degradation and replacement cost while others reveal that the combination of peak shaving, and cost reduction if grid components faults can even reach a net value of 20,000 Euros [77, 78]. A refer-

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ence [79] even mention that battery life can be extended as idling is causing more damage to the cells. It is also concluded that if the battery replacement cost is maintained below the threshold of 100 Euros per kWh then V2G implementation is viable for commercial vehicles like electric buses or vans [80]. This project is highly dependable on the newer battery technologies expected in the next few years that will inherit higher energy density and safety with lower price in mass-production [44]. Therefore the V2G scheme has to be studied adequately as it shows a promising pattern for the future of electricity market.

The electricity market is evolving rapidly hence the application of a precision meter with reliability and granularity necessary. This method of energy metering is called AMI (Advanced Metering Infrastructure) and provides real-time information for the utility grid and the aggregator. Using this data, AMI can improve the quality of the electricity grid and ensure the reliability of the Vehicle-to-Grid system [81]. The grid operator monitors this layout to ensure undisrupted power supply and safety. Nevertheless, it is expected that there will be delays in the exchange of information data between the electric vehicle and the utility grid, considering the duration of communication required [70, 82]. The emergence of bidirectional charging systems further enhances a smooth transition in electric mobility, enabling a two-way energy transfer between the electricity grid and EVs. As the need for electric vehicles' autonomy and their dominance in the market accelerates, bidirectional charging systems that are balanced can revolutionize energy management, leading to a more sophisticated, clean, and efficient transportation platform [83].

6. Conclusions

The transition to electric vehicles (EVs) is a pivotal step in the global effort to combat climate change and reduce greenhouse gas emissions. As the transportation sector is one of the largest contributors to carbon emissions, over 28%, shifting from traditional internal combustion engine vehicles to EVs can significantly lower the overall carbon footprint. This transition is not only essential for meeting international climate goals but also for enhancing energy efficiency within the transportation sector. The environmental benefits of transitioning to electric vehicles extend beyond just reducing greenhouse gas emissions. By reducing tailpipe emissions, electric vehicles can help decrease the prevalence of respiratory diseases and other health issues associated with poor air quality. In conclusion, the transition to electric vehicles is not merely a technological shift; it represents a comprehensive approach to creating a more sustainable and efficient transportation system. While challenges remain, the advancements in technology, the expansion of charging infrastructure, and the potential for integration with the energy grid all point toward a future where electric vehicles play a central role in reducing emissions, enhancing energy efficiency, and improving public health. As society continues to embrace this transition, the collective efforts of governments, industries, and consumers will be crucial in realizing the full potential of electric vehicles for a sustainable future.

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The integration of EVs into the energy grid presents additional opportunities for sustainability and can help balance the load curve, particularly during peak usage times. Additionally, vehicle-to-grid (V2G) technology enables EVs to return energy to the grid, further enhancing grid stability and promoting the use of renewable energy sources. Moreover, the growing infrastructure for charging stations is a critical component of this transition. Charging networks expansion is allowing more users to adopt EVs, alleviating range anxiety and ensuring that charging is convenient and accessible This paper provides a comprehensive analysis of the impact of electric vehicle (EV) charging stations on the electricity utility grid, highlighting both the opportunities and challenges they present.

Electric vehicles significantly reduce energy waste by over 300% compared to conventional vehicles, offering a substantial reduction in greenhouse gas emissions. Technological advancements in battery technology and electric drivetrains have made EVs more accessible and appealing to consumers. Lithium-ion batteries, which dominate the EV market, are recognized for their high energy density, reliability, and longevity. However, challenges such as aging and thermal performance remain critical but ongoing research and development in battery technology, including solid-state batteries and alternative materials for the cahtode, hold promise for overcoming these limitations. In addition recent advancements in charging technology have reduced charging times to as low as 10–15 minutes for 80% capacity using high-voltage systems, with DC fast chargers delivering power levels up to 120 kW and voltages ranging from 320 volts to 500 volts.

The integration of Vehicle-to-Grid (V2G) technology was identified as a pivotal development, enabling bidirectional power flow and reducing peak grid loads by over 4%. V2G systems also contributed to a 40% reduction in energy costs and a 14% decrease in EV scheduling costs, while enhancing grid stability and enabling real-time energy exchanges. The market potential for V2G technology is substantial, with an estimated growth to $52 million by 2030 at an annual growth rate of 28%. Economic analyses [77–79] show that peak-to-valley arbitrage using EVs can yield significant cost benefits, particularly when battery replacement costs are maintained below €100 per kWh, ensuring commercial viability.

The study highlights the critical need for robust charging infrastructure to support the growing EV market. Behavioral patterns of EV users show that vehicles are parked 95% of the time, offering a largely untapped resource for energy exchange. Time-of-use tariffs, such as those in China, which offer discounts of up to 75% for off-peak charging, demonstrate the potential for influencing charging behaviors to reduce grid stress. Despite these advances, the study identifies challenges that must be addressed, including ensuring data privacy, enhancing communication reliability, and mitigating battery degradation due to increased charge-discharge cycles. Advanced battery management systems (BMS) are identified as a key solution to many of these issues.

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The contribution of this paper to the EV field is the detailed examination of the integration of EVs into utility grids, emphasizing the technological, environmental, and economic dimensions. It provides quantified insights into the benefits of V2G systems in reducing grid stress, improving energy efficiency, and promoting the use of renewable energy sources. Furthermore, the paper highlights the importance of advanced battery technologies and charging infrastructure in supporting the sustainable expansion of electric mobility. By addressing technical challenges in communication protocols, battery performance, and grid reliability, this study paves the way for future research and technological advancements. Overall, this work underscores the transformative potential of EVs and V2G systems in achieving a sustainable and efficient energy future.

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