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Empowering Electric Vehicle Charging Infrastructure with Renewable Energy Integration

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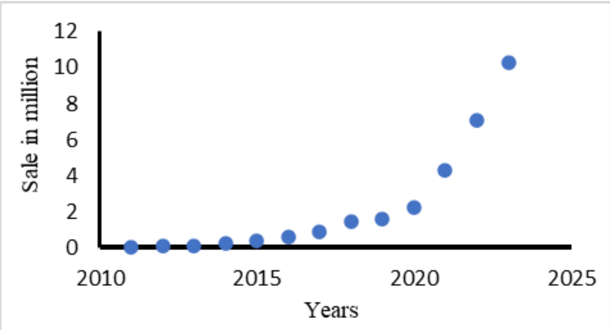
***Abstract*— *The escalating energy crisis, heightened environmental awareness and the impacts of climate change have driven global efforts to reduce carbon emissions. A key strategy in this transition is the adoption of green energy technologies particularly for charging electric vehicles (EVs). According to the U.S. Department of Energy, EVs utilize approximately 60% of their input energy during operation, twice the efficiency of conventional fossil fuel vehicles. However, the environmental benefits of EVs are heavily dependent on the source of electricity used for charging. This study examines the potential of renewable energy (RE) as a sustainable alternative for electric vehicle (EV) charging by analyzing several critical dimensions. It explores the current RE sources used in EV infrastructure, highlighting global adoption trends, their advantages, limitations, and the leading nations in this transition. It also evaluates supporting technologies such as energy storage systems, charging technologies, power electronics, and smart grid integration that facilitate RE adoption. The study reviews RE-enabled smart charging strategies implemented across the industry to meet growing global EV energy demands. Finally, it discusses key challenges and prospects associated with grid integration, infrastructure upgrades, standardization, maintenance, cybersecurity, and the optimization of energy resources. This review aims to serve as a foundational reference for stakeholders and researchers seeking to advance the sustainable development of RE based EV charging systems.*

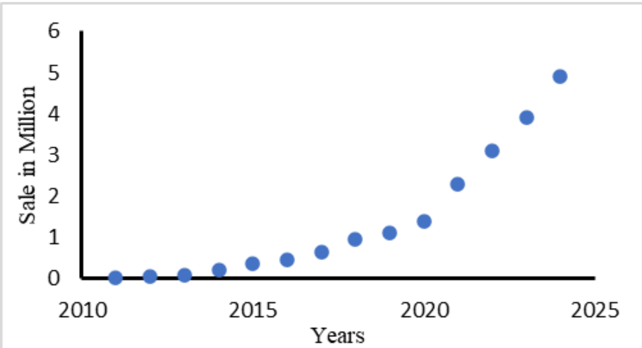
***Keywords*— RE, EVCS, EV, Carbon Emission, cybersecurity.**

I. INTRODUCTION

As nations continue to evolve across various sectors—including infrastructure, automation, transportation, and technology, there is a corresponding rise in the emission of harmful substances into the environment. Alongside emissions from industrial activity, transportation has become a significant contributor to greenhouse gases, which are a primary driver of global climate change and increasing global temperatures [1-4]. Recent data indicates that the transportation sector is responsible for approximately 25% of total carbon dioxide emissions in European countries and about 32% in the United States [5-6]. These figures highlight the pressing need to address pollution from transportation sources, particularly because the energy demands of this sector are overwhelmingly met through fossil fuel consumption. In response to mounting environmental concerns and the urgent call for climate action, governments around the world are implementing strategies to reduce carbon emissions and adopt sustainable energy alternatives. This push toward sustainability has encouraged automotive manufacturers to invest heavily in the research and development of electric vehicles (EVs) [7]. EVs are increasingly seen as a cleaner alternative to traditional internal combustion engine vehicles and a viable path to achieving global carbon neutrality. The global market for electric vehicles has witnessed a significant upsurge in recent years. For example, EV sales in 2021 doubled compared to the previous year [8-9]. Europe saw a notable increase, with more than 2 million EVs sold in the first quarter of 2022 alone, marking a 75% rise compared to the same period in 2021. Forecasts suggest that global EV sales will expand nearly tenfold by the end of this decade, reaching around 19 million units and accounting for over 7% of all vehicles on the road by 2030 [7]. Figure 1 (a) shows the global sale trend of BEV and (b) shows the global sale trend of PHEVs from 2011 to 2024.



(a)



(b)

Fig. 1 (a) Global trend of BEV sales, (b) Global trend of PHEVs sales [10]

With the anticipated increase in EV adoption, electricity demand is also projected to rise. By 2030, global power demand is expected to climb by approximately 4%, primarily driven by the proliferation of electric vehicles. Addressing this growing demand without overburdening the electricity grid will require a careful blend of renewable energy sources and conventional power plants. Renewable energy technologies particularly wind and solar are among the fastest-growing in the energy sector and are projected to contribute over 35% of global electricity by 2050 [11].

The integration of renewable energy (RE) into the transportation sector, especially for EV charging, presents both opportunities and challenges. The vision for 2050 includes a net-zero carbon economy with dependable, affordable, and universally accessible energy. This transition will be powered by a dynamic and cost-effective renewable energy infrastructure [12]. Advanced innovations such as vehicle-to-grid (V2G) technologies are playing an essential role in reducing renewable energy costs and making low-cost charging more accessible. V2G systems allow electric vehicles not only to draw power from the grid but also to supply energy back, turning EVs into distributed energy storage units. These vehicles can provide valuable ancillary services such as managing peak loads, maintaining voltage stability, and supporting grid frequency regulation. The integration of renewables into the power grid has accelerated significantly in recent years, particularly with the addition of solar photovoltaic (PV) and wind energy systems. However, the intermittent nature of these energy sources poses challenges for ensuring reliable and consistent power for EV charging [13]. As a result, the adoption of supportive policies, smart charging infrastructure, and advanced power management technologies has become critical for efficient energy distribution.

Recent advancements in power electronics and fast-charging technologies have substantially enhanced the efficiency and convenience of EV charging. These technologies have reduced charging times and improved overall energy optimization. Despite these advancements, unmanaged or uncoordinated EV charging behavior can place considerable stress on utility grids, potentially compromising grid stability and capacity [14]. To prevent these issues, intelligent charging solutions must be adopted. Smart charging systems, which allow utilities to control charging schedules based on grid load and renewable energy availability, are key to minimizing the negative impact on the grid [15]. Strategic planning of charging station networks, incorporating both existing power generation facilities and new renewable installations will be essential to meet future energy needs. However, the expansion of urban areas and the widespread adoption of EVs create logistical challenges. Managing the charging schedules and energy distribution across large geographic regions is complex and often exceeds the capabilities of a single energy aggregator. This complexity necessitates the development of

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sophisticated, decentralized energy management systems [16].

Governments worldwide are actively promoting the shift from traditional energy sources to renewables including solar, wind, hydro, bioenergy and tidal power. In the United States, several energy providers have made public commitments to transition entirely to renewable energy. For example, Austin Energy has launched the "Plug-in Everywhere Network," enabling EV owners to power their vehicles with 100% renewable energy, particularly wind. Similarly, EV go, which operates a nationwide fast-charging network has announced its plan to power its entire network with wind or solar energy. Additionally, Pacific Gas and Electric in partnership with BMW has launched the Charge Forward program, which provides financial incentives to EV owners who align their charging behavior with periods of high renewable energy availability [17]. These initiatives are designed to address the additional demand that EVs place on the electrical grid. A variety of strategies have been proposed to mitigate the impact of this demand, such as flexible charging schedules, energy storage systems, dispatchable loads, and the development of alternative power generation capacity [18]. As these solutions depend heavily on the integration of EVs into the electrical grid, their successful deployment will play a pivotal role in promoting the broader use of renewable energy.

In the academic and industrial sectors, there has been a surge of research exploring the integration of renewable energy with EV charging technologies. Some studies have focused on developing optimized EV charging schedules that align with renewable energy availability, while others have proposed automated pricing mechanisms that reflect real-time energy costs. Further investigations have delved into V2G and smart charging applications aimed at improving power regulation, maintaining grid stability, and enhancing power quality and reliability [19]. Recent literature also includes cost-benefit analyses of vehicle-to-home (V2H) applications, which allow EVs to power residential loads during peak hours or outages. While there is extensive research on various elements of renewable energy integration with EV charging systems, a unified and holistic framework is still lacking. This gap underscores the need for comprehensive studies that not only assess current technologies but also provide actionable insights for future improvements [20]. To address this need, our review consolidates the most current advancements in EV charging infrastructure, renewable energy-enabled charging techniques, and associated challenges. It aims to provide a foundational reference for researchers, policymakers, and industry professionals working toward sustainable mobility solutions [21]. Key contributions of this work including, an in-depth examination of renewable energy-based EV charging systems, encompassing the infrastructure, enabling technologies and integration with the power grid. A detailed analysis of smart charging strategies currently being implemented in the industry. These include network-based charging, time-shifted charging, excess renewable utilization, on-site renewable charging and managed charging, each tailored to align EV charging demand with renewable energy generation. Insights into the growing interest among utility providers in renewable energy along with various options available to EV users to maximize the benefits of RE-based charging. This includes cost-effective solutions tailored to different vehicle types and charging patterns. A discussion on the primary challenges and potential future directions for research and development. These include technical barriers, economic considerations, policy implications and emerging opportunities in intelligent energy management and grid modernization.

II. EVCS INFRASTRUCTURE

The integration of electric vehicles (EVs) with existing renewable energy (RE) sources can influence the performance and stability of the utility grid. This review specifically examines solar and wind energy as feasible options for EV charging, given their variable nature. Hydropower is excluded from the scope of this study due to its consistent energy output, which differs from intermittent sources [22]. Despite steady growth in electric vehicle (EV) adoption worldwide, limited charging infrastructure continues to hinder widespread acceptance. Expanding public charging stations and increasing awareness about sustainable mobility are essential steps toward overcoming this barrier. Effective implementation requires careful planning, including geographic surveys and strategic site selection. The growing presence of EVs also introduces new dynamics across several sectors. In the electric power market, increased charging demand poses challenges for the grid, but EVs offer unique benefits through their battery storage capabilities, enabling services like vehicle-to-grid (V2G) to support grid stability [23]. In the transportation sector, the convergence of power distribution and mobility

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networks has sparked collaborative efforts between energy and transportation stakeholders [24]. Meanwhile, in distribution system planning, uncoordinated placement of charging stations can lead to higher power losses and degraded voltage profiles, making optimized infrastructure planning crucial for secure and efficient grid operation. To support the additional load, renewable energy (RE) sources such as solar, wind, and biomass offer environmentally friendly alternatives. However, their intermittent nature limits reliability. To mitigate this, energy storage technologies and adaptive load management strategies can help balance supply and demand. Innovative systems like supercapacitors and flywheels are emerging as promising solutions for enhancing RE integration into EV charging networks [25].

One major challenge with renewable energy (RE) is its intermittency, energy must be used immediately or sent to the grid to avoid losses. To address this, researchers advocate for stationary energy storage and fast-charging systems, which enhance the reliability of EV charging by providing backup energy when needed. Among energy storage technologies, lithium-ion batteries dominate with 76% of global electrochemical storage capacity, followed by sodium-sulfur, lead-acid, and redox flow batteries [26]. Alternatives like nickel-metal-hydride and nickel-cadmium offer recyclability and reliable performance. Supercapacitors (SCs) or ultracapacitors (UCs), which store energy electrostatically, offer longer lifespans and significantly higher power density compared to conventional batteries but require advanced control systems due to their fast charge-discharge behavior. Flywheel Energy Storage (FES), which stores kinetic energy mechanically is especially useful in wind-based RE systems [27]. Hybrid Energy Storage Systems (HESS), combining batteries with UCs or fuel cells, optimize both energy and power density, managing low- and high-frequency fluctuations in RE output. These systems are often integrated using bidirectional DC-DC converters to regulate power flow between sources and loads, forming the backbone of efficient, grid-connected RE-based charging infrastructures [28]. Figure 2 explore the EVCS Infra integrated with renewable energy (RE) and energy storage.

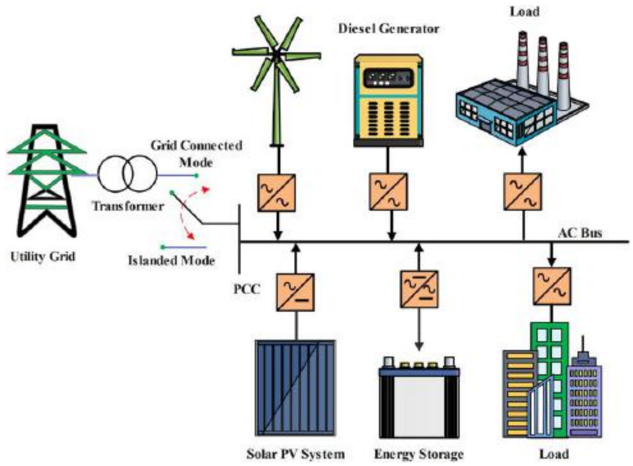

Fig. 2 EVCS Infra integrated with renewable energy (RE) and energy storage [29]

The rising number of electric vehicles (EVs) puts increasing pressure on the power grid, necessitating upgrades in distribution infrastructure and network capacity. Instead of costly enhancements for occasional peak loads, optimizing energy use across the full day is more efficient. Emerging technologies like bidirectional vehicle-to-grid (V2G) offer solutions by enabling controlled energy flow between EVs and the grid. V2G enables energy to flow both ways, letting EVs supply power back to the grid especially beneficial when combined with renewable energy. This supports grid stability and allows EV owners to earn from surplus energy [30]. As EV adoption grows, smarter charging systems and upgraded infrastructure are essential. Technologies such as V2B, V2H, V2N, and V2X further enhance renewable energy integration and grid efficiency [31].

III. RE INTEGRATED SMART CHARGING

Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) consume between 500 and 4,400 kWh annually, while electric buses and trucks use approximately 0.57 to 3.35 kWh per mile [32]. The U.S. National Renewable Energy Laboratory projects EV energy demand could reach 300 TWh by 2030 [33]. In response, utilities have begun integrating renewable energy (RE) into EV charging through initiatives like green tariffs, community solar projects, and renewable energy certificates. However, these programs often overlook EV-specific loads and do not fully align charging times with renewable generation. To address this, utilities and third parties are developing smart charging strategies, such as off-peak incentives, time-based pricing, and direct RE access [34]. Utilities are

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adapting to the growing demand for EVs and renewable energy by introducing new pricing models and programs that support RE-based charging. In the U.S., initiatives like green tariffs and community solar programs have historically enabled customers to source renewable electricity, though these were not specifically designed for EV charging. As a result, they often overlook the unique, variable demands of EVs. Recently, utilities have launched targeted programs mainly for light-duty vehicles that better align EV charging with grid needs and renewable availability. This section reviews smart charging strategies and the associated utility and third-party initiatives that help synchronize EV charging with renewable energy supply. Figure 3 shows the infrastructure of Electric vehicles charging with renewable energy.

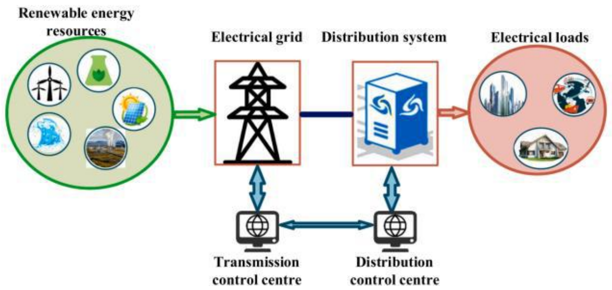

Fig.3: Electric vehicles charging with renewable energy [35]

Network charging is a smart solution that allows EV users to charge their vehicles with electricity sourced from renewable energy (RE). Although many charging stations exist, few offer power exclusively from RE. These programs let users subscribe to a set amount of RE-backed charging, often encouraging off-peak charging especially at night when wind energy is more abundant [36]. Pricing options vary, including pay-as-you-go, fixed monthly rates, government-subsidized plans, and workplace agreements. Participation typically requires registration through a utility or charging network [37]. A notable example is Austin Energy's Plug-in Everywhere Network, which supplies charging power entirely from wind energy. Network charging strategies aim to reduce carbon emissions while supporting technologies like demand response and energy storage [38]. These methods focus on avoiding peak-hour charging, aligning EV charging with renewable energy (RE) generation, and enhancing user satisfaction through affordable, flexible options. Utilities use various tools such as incentives, behavioral programs, and EV telematics to guide consumer behavior but pricing strategies, especially time-of-use (ToU) rates are the most effective. ToU rates encourage off-peak charging without the complexity of real-time pricing [39].

IV. CHALLENGES AND PROSPECT

The transportation sector is undergoing a transformative shift towards sustainability, driven by advancements in electric vehicles (EVs), renewable energy (RE), and smart grid technologies. While RE integration with EV charging offers significant environmental and economic benefits, it also introduces several technical, infrastructural, and policy challenges that must be addressed to ensure scalability and long-term reliability [40]. One of the foremost challenges is grid integration. As EV adoption accelerates, especially in urban centers, utility grids face increasing stress due to high charging loads. Smart solutions such as vehicle-to-grid (V2G) and vehicle-to-home (V2H) technologies offer some flexibility, but large-scale implementation will require major upgrades in grid infrastructure, demand-response systems, and energy storage technologies. Closely related is the need for infrastructure renovation. Existing residential, commercial, and public spaces are not always equipped to support high-capacity EV charging, especially when powered by on-site renewables. Remote areas and highways also pose logistical hurdles for reliable fast-charging access [34].

Another pressing issue is the lack of transparency in distribution networks, particularly at medium and low voltages. Inadequate real-time load data hampers planning and optimization. The adoption of smart meters and integrated monitoring systems is critical for seamless energy management across RE sources, EVs, and utility grids. In parallel, a fragmented regulatory framework limits the ability of power distributors and consumers to contract flexible services. Enabling market participation from smaller consumers and distributed systems requires supportive policies, simplified entry standards, and improved market awareness [41]. Standardization gaps especially in connectors and communication protocols for two- and three-wheelers, also impede EV interoperability and user convenience. The absence of universal standards restricts access to charging networks and slows market growth. Additionally, maintenance complexity has surged with the integration of RE into smart grids, demanding continuous technical support and skilled personnel to manage system updates, failures, and reconfigurations.

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Biodiversity impacts from RE infrastructure deployment—such as land degradation, wildlife disruption, and increased carbon emissions during equipment transport and installation—pose environmental challenges. Similarly, electronic waste management remains a concern due to limited recycling solutions for RE and EV components. The industry's growing dependence on rare earth minerals for batteries exacerbates supply chain risks, especially when high-quality ores are scarce or difficult to extract sustainably. Security is another critical area. Cybersecurity threats to smart charging infrastructure jeopardize user data, transaction safety, and system integrity. Robust legal frameworks and secure communication protocols are essential to safeguard these interconnected networks [42]. Moreover, the intermittent nature of RE sources can limit charging availability, especially during peak demand or low generation periods. Proper planning and grid coordination are necessary to maintain service reliability. The Emerging challenges include user behavioral unpredictability and urban planning constraints are also more crucial. Users' diverse charging habits and lack of awareness regarding optimal charging times can disrupt grid load balancing and limit the effectiveness of time-of-use incentives [43]. Meanwhile, integrating EV charging infrastructure into dense urban environments with limited space and legacy systems requires innovative architectural and logistical solutions. The resource optimization across energy, digital, and human domains remains a core challenge [44]. The complexity of managing interconnected systems ranging from IT platforms to power hardware demands substantial investment in both technology and skilled labor, pushing up the cost of deployment. Addressing these multifaceted challenges requires coordinated action from governments, industries, researchers, and consumers to build a resilient, inclusive, and sustainable EV charging ecosystem.

V. Conclusion

The transition from fossil-fueled vehicles to electric vehicles (EVs) powered by renewable energy (RE) is essential for sustainable mobility. Driven by policies and consumer awareness, automakers are shifting from internal combustion engine vehicles to EVs, which offer benefits like energy efficiency, quiet operation, and eco-routing. Smart charging systems optimize power use through intelligent algorithms, support both public and private infrastructure, and enhance grid stability. Integrating RE sources such as solar and wind into charging networks lowers costs and boosts efficiency. Time-based tariffs further encourage off peak charging. Expanding charging infrastructure and ensuring system interoperability are critical as EV adoption grows. Policymakers must support this shift with incentives, funding, and education. Strategic planning tools, like grid capacity mapping help guide infrastructure development. Continued innovation is vital to meet evolving energy and mobility needs.

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