

Integration of Renewable Energy and Artificial Intelligence in Electric Vehicle Charging: A Review of Smart Grid-Connected Systems

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Abstract: The emerging integration of renewable energy sources and artificial intelligence implementation in EV charging infrastructure seems to be perhaps an important remedy for decarbonizing transportation and modernizing power systems. This is a study designed to investigate the entire scenario of electric vehicle charging technologies and the trend from orthodox systems to smart grid-connected, intelligent charging network schemes. Coverage will also include the technical architecture of such renewable-powered charging systems, such as standalone, grid-tied, and hybrid designs, with the use of energy storage systems and bidirectional power flow integration. Predictive maintenance, load forecasting, dynamic pricing, and demand-side optimization aspects of EV charging will also be included in this study as among the changing roles expected of AI in EV charging. This study also discusses the issues related to the renewable intermittency, high upfront installations cost, limited spread of infrastructure, and cybersecurity risks posed by AI-driven systems. Besides collating analysis of recent developments with the emerging trends, it also flags out gaps and barriers in research and policy, calling for multilateral cooperation and strong regulatory frameworks. However, for efficiency of systems, greater resilience of grids, greater capacity for long-term carbon emission offsetting, and primarily, effective transition into sustainable urban mobility and climate action, these two aspects are recognized as being mutually beneficial i.e., AI plus renewables within EV charging.

Keywords: Electric Vehicles, Renewable Energy, Smart Grid, Artificial Intelligence, V2G, Load Management, Charging Infrastructure, Energy Storage, Demand Response, Cybersecurity

I INTRODUCTION

The conventional transportation system that incorporates an internal combustion engine (ICE) is the major contributor to air pollution. To reduce air pollution and oil dependence in the transportation sector, there has been an increased overall market adoption of electric vehicles (EVs) in recent years. EVs use batteries, ultracapacitors, and fuel cells as energy sources, which have no dependency on fossil fuel and no polluted gas emission [1]. The increase in electric vehicles (EVs) is encouraged worldwide. The aim is to reduce the impact of the transport sector on global climate change, as well as to reduce local air pollution, especially in urban areas. Countries are looking for ways to increase economic growth through the introduction of battery electric vehicles (BEVs) or hybrid ones (PHEVs). This can be achieved through EV manufacturing, deployment of EV charging infrastructure and systems for management and payment of electrical loads in the charging stations. Along with the benefits of their implementation, the EVs also pose a challenge to the use and maintenance of electrical networks. Two problems can be outlined: capacity of the electricity networks, especially at distribution level, where the possible limit of the power supply network can be reached for the supply of new electricity consumers, and the ways of payment and management of the EV charging process [2].

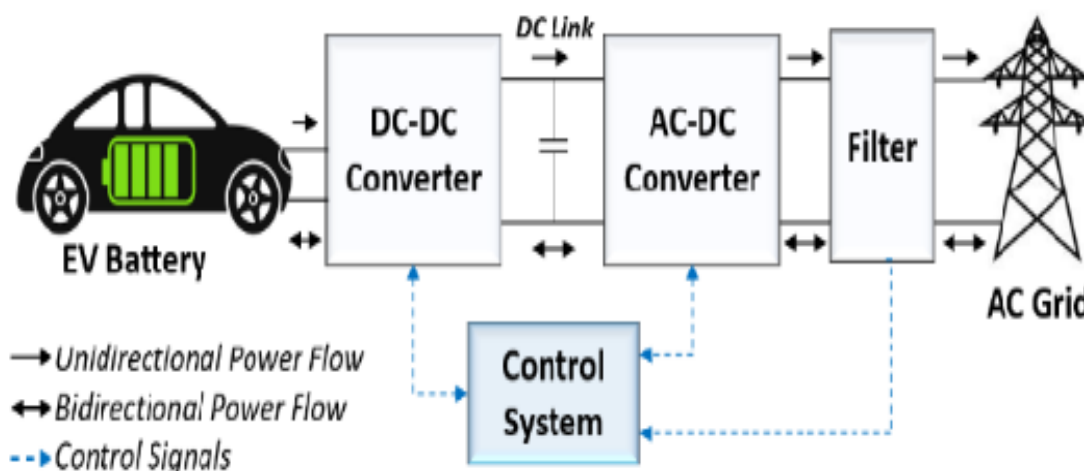


Fig. 1 Block diagram of conventional EV charging system [3]

Figure 1 shows a bidirectional EV charging system where power flows between the EV battery and the AC grid through DC-DC and AC-DC converters, coordinated by a central control system. The DC link connects the converters, while a filter ensures power quality before grid interaction. Solid arrows indicate power flow directions, and dashed lines represent control signals that enable efficient energy management and grid support functions like V2G.

The evolution of EV charging infrastructure is now moving from basic home installations to smart grid-integrated systems. Charging used to be limited to Level 1 AC systems, where household outlets (120V) were the only means of charging, offering extraordinarily slow single-direction charging without any form of communication between the charger and the vehicle. Charging times would exceed 12 hours, often with little to no coordination with the power grid [4]. With the rapid adoption of EVs, Level 2 AC and DC fast (Level 3) charging stations came along, resulting in the dramatic shortening of charging time. Standardization of connectors, compatibility with mobile apps, made the use of such charging more convenient [5]. However, mostly, they were passive and not connected towards real-time grid operations. The newest generation has become smart charging, which is two-way, real-time-tracking integrated charging with renewable energy and energy storage systems. Some advanced functions, such as vehicle-to-grid (V2G), dynamic load management, and AI-based optimization, have all become part of these new standards for charging, allowing charging to proceed in a more efficient and flexible way [6]. Future developments are going to include autonomous wireless systems, block-chained energy trading, and decentralized microgrids into future infrastructures, making it easier for energy resilience to be achieved, increased convenience to the end-users, and lots more in grid support with the increasing adoption of EVs [7].

The motivation to merge renewable energy and artificial intelligence (AI) in electric vehicle (EV) charging has arisen from the dual need of reducing carbon emissions and enhancing energy efficiency. As the electric transportation sector brings forth a new paradigm, the need arises to ensure that EV charging uses clean energy sources such as solar and wind to enhance the overall environmental benefits and reduce dependence on fossil fuels [8]. However, the inherent intermittency of renewable energy sources creates challenges in providing an uninterrupted supply of power and achieving grid stability. AI essentially creates avenues for smart energy management by forecasting demand, predicting renewable generation, optimizing charging schedules, and enabling real-time load balancing [9]. This includes ML, neural networks, and reinforcement learning to ensure that charging operations dynamically adapt according to user behavior, grid conditions, and economic price signals. Renewables, when used in combination with AI-based control, assure EV charging systems that are sustainable, economic, and amenable to the grid. This will foster a truly resilient energy ecosystem and enhance the worldwide momentum of transitioning cleanly to mobility [10].

II Renewable Energy Integration in EV Charging Systems

Interconnection of renewable energy sources, particularly solar and wind, into electric vehicle (EV) charging systems is driven by the need to reduce carbon emissions and reliance on fossil fuels. Solar photovoltaic systems are most widely and frequently deployed renewable source of energy because they can be used in a scalable way, they are becoming cheaper, and they are amenable to rooftop or ground-mounted applications [11]. In countries or regions where there are consistent patterns of winds, wind energy generates a complementary profile to the generation, and this is mostly applied for larger-sized or hybrid configurations. Other renewables such as biomass and hydro energy are less commonly practiced but have relevance in certain cases. These renewables coupled with energy storage systems and smart controls in offer cleaner, more practised, and cheaper EV charging solutions [12]. Generally, three architectures can categorize renewable-powered EV charging systems: grid-tied, hybrid, and stand-alone systems. The term independent systems refer to completely autonomously functioning systems whose entire energy supply comes from renewable sources (like solar or wind) with supplementary battery backup [13]. These systems usually find widespread application in remote or off-grid locations, where limited access to the grid is available. With energy independence and no emissions during operation, renewable energy systems have intermittency associated with them and require larger storage capacities to maintain their reliability, which increases costs. They are not very scalable, limiting them to lower demand or isolated installations [14].

Grid-tied systems connect the utility grid, enabling access to the grid when renewable generation is low, while returning excess generation to the grid when supply exceeds demand. This ensures a more diversified energy supply, reduces the need for storage, and allows for participation in grid support programs. However, they are dependent on availability and stability of the grid [15]. The hybrid system is a combination of both grid and standalone because it integrates renewable energy sources with battery storage and grid connectivity. This would offer the most flexibility by ensuring continuous charging, optimizing energy use, and offering a grid-independent operation during outages. Hybrid installations have a high initial capital investment; however, they are considered the most robust and adap [16]. The desirable characteristics of an energy storage system (ESS) to fulfill the energy requirement in electric vehicles (EVs) are high specific energy, significant storage capacity, longer life cycles, high operating efficiency, and low cost. Energy storage systems (ESS) for EVs are available in many specific figures including electro-chemical (batteries), chemical (fuel cells), electrical (ultra-capacitors), mechanical (flywheels), thermal and hybrid systems [17].

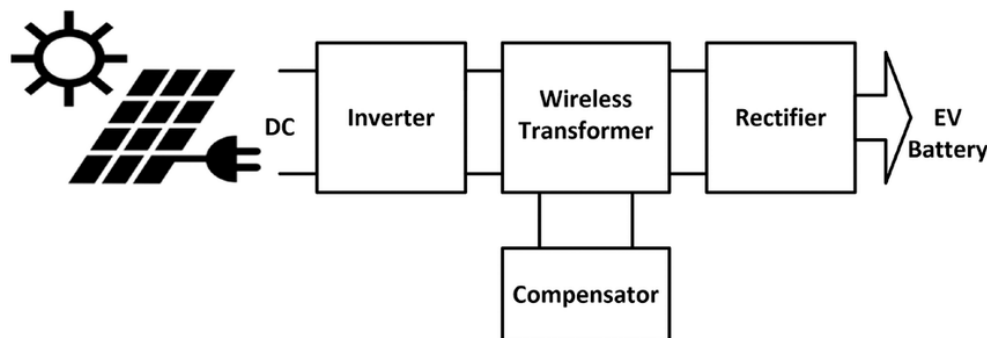


Fig. 2 Renewable energy powered EV block diagram [18]

Figure 2 illustrates a renewable energy-powered electric vehicle (EV) charging system using wireless power transfer. Solar energy is harvested through photovoltaic panels and supplied as DC power to an inverter, which converts it into high-frequency AC. This AC power is transmitted via a wireless transformer, enabling contactless energy transfer to the receiving side. The rectifier then converts the AC back to DC for charging the EV battery. A compensator is included to enhance power transfer efficiency and maintain system stability by managing reactive power. This setup enables clean, efficient, and convenient wireless EV charging using renewable energy.

Challenges come to life with regard to renewable energy sources like solar and wind for electric vehicle (EV) charging systems. Certainly, one of the biggest problems facing energization by renewable generation is intermittency. The fact is that generation from renewable sources is typically variable and environment-dependent, complicating coordination of energy production from renewable sources with demand from EVs in real time. For example, EVs would typically be charged at night or late at night, while the peak for solar power is during midday, leaving a mismatch between generation and consumption of energy [19]. Left without storage systems and intelligent grid relationships, mismatches would inevitably bring about the inefficient utilization of energy, over-reliance on the grid, and inadequate charging availability during the most demanding times of the day. This unpredictability adds to the burdens of charge energy planning and detracts from the overall reliability of renewable-powered EV charging networks. Another obstacle to renewable integration includes all these initial upfront capital costs required [20]. The cost of renewable technologies has definitely declined over the years, but the actual amount of capital needed, in the upfront count, is still high for renewable technologies, with photovoltaic, wind turbine, inverter and smart meters, and battery storage systems being some of their examples. This becomes a burden in terms of financing those requiring that charging infrastructure be public or privately owned, but it becomes quite dissuading for most areas with limited policy incentives or subsidies. Existing problems in infrastructure add to the complexity. Many of the local grids are engineered for older towns or remote areas and are ill-equipped to radiate large quantities of electricity quickly [21].

III Artificial Intelligence Applications in EV Charging Management

AI technology has transformed electric vehicle (EV) charging systems, improving user experience, reliability, and efficiency. AI algorithms improve charging plans using real-time power use, grid capacity, and user behavior. This allows EVs to charge at the ideal periods, when renewable energy is abundant and electricity prices are low, reducing costs and environmental effects [22]. Machine learning-based predictive maintenance monitors charging infrastructure for problems and inefficiencies before they occur, reducing downtime and improving reliability. AI-driven smart grids may integrate EVs into energy management plans to balance system loads and participate in demand response. AI provides real-time charging station availability, specialized charging suggestions, and dynamic pricing schemes that incentivize off-peak charging, improving customer convenience [23]. The growing use of Battery Electric Vehicles (BEVs) in residential areas will impact power demand, necessitating detailed research on distribution network planning and load profiles. Uncontrolled high-power EV charging, like 11.1 kW and 22.2 kW, can overload the grid [24]. To manage this demand, AI-based Demand Response (DR) algorithms are essential. Unlike traditional methods that involve costly and environmentally harmful infrastructure expansion, AI-based DR uses machine learning and advanced analytics to align EV charging with available supply [25]. In high-rise residential complexes with limited electrical capacity, AI DR systems help balance EV charging and prevent grid strain. By adjusting charging schedules based on driver behavior, these systems can lower greenhouse gas emissions, reduce power costs, and enhance system stability. Optimization algorithms such as Artificial Neural Networks (ANN), Dynamic Programming (DP), Fuzzy Logic (FL), Game Theory, and Particle Swarm Optimization (PSO) are used to minimize consumer costs, transformer loads, energy prices, network losses,

voltage variations, and peak loads, improving the economic feasibility of EV integration [26]. Additionally, integrating individual user behavior and dynamic factors with system capacities remains a challenge. Advanced AI algorithms like Deep Reinforcement Learning (DRL) and ANN show promise in addressing these issues, especially when considering discharging features and unpredictable charging rates [27].

Charging stations enabled by artificial intelligence utilize sensors and communication capabilities to collect up-to-the-minute information on vehicle charging habits, grid demand, and energy costs. This information serves as the foundation for optimizing the charging process. Vehicle-to-Grid (V2G) technology facilitates the exchange of energy between electric vehicles (EVs) and the power grid in both directions. Artificial intelligence algorithms employ vehicle-to-grid (V2G) capabilities to regulate electric vehicle (EV) charging in response to fluctuations in grid demand and supply, effectively maintaining a harmonized energy usage [28]. AI systems, especially those related to machine learning, demonstrate exceptional proficiency in recognizing patterns and generating predictions by leveraging past data. When utilized for electric vehicle charging, these algorithms can assess variables such as user conduct, charging station accessibility, and energy costs to generate precise forecasts regarding charging needs. Through the application of predictive analytics, AI algorithms can suggest the most advantageous times and durations for charging to customers, guaranteeing the efficient use of charging infrastructure while minimizing expenses and strain on the power grid [29]. AI algorithms depend on comprehensive data gathering and analysis. Safeguarding user privacy and ensuring the protection of sensitive charging data is of paramount importance. It is crucial to implement strong data protection procedures and comply with strict privacy requirements [30]. The integration of solar and load forecasts with AI supports intelligent decision-making, optimizing energy use even under varying supply and demand conditions [31]

Table 1 Comparative Summary of AI Applications in EV Charging

Reference	Focus Area	Key AI Techniques	Applications in EV Charging	Remarks
[22]	Smart charging optimization	Real-time optimization, predictive analytics	Timing EV charging during low-cost, high-renewable periods	Improves cost-efficiency and reduces environmental impact
[23]	User experience and dynamic pricing	Machine learning, recommender systems	Charging suggestions, station availability, dynamic pricing	Enhances convenience and encourages off-peak charging
[24]	Grid impact and residential demand	Demand Response (DR), load profiling	Prevents grid overload in high-rise and residential zones	Addresses uncontrolled high-power EV charging
[25]	Infrastructure management via AI	DR algorithms, analytics	Avoids infrastructure expansion by aligning charging to supply	Cost-effective grid management solution
[26]	Optimization methods	ANN, FL, PSO, DP, Game Theory	Minimizes costs, transformer load, voltage issues, and energy losses	Multi-objective economic and technical optimization
[27]	Advanced learning for uncertain environments	DRL, ANN	Handles unpredictable charging rates, user behavior, and discharging control	Enables intelligent, adaptive scheduling
[28]	V2G integration and communication systems	AI-controlled V2G, sensor networks	Balances grid supply/demand via bi-directional energy flow	Improves grid reliability and EV utility
[29]	Predictive modeling and forecasting	Predictive analytics, behavioral modeling	Suggests optimal charge durations and timing; manages battery usage	Reduces grid strain and improves user savings
[30]	Data privacy and security	Privacy-preserving AI	Protects sensitive user and energy consumption data	Ensures compliance and user trust
[31]	Renewable and load forecasting integration	AI with solar/load forecasting	Enables intelligent charging decisions under fluctuating supply and demand	Supports renewable-based charging and system efficiency

IV Smart Grid-Connected EV Charging Systems

Electric vehicles utilize power in so many ways, systems that rely on them are prone to problems. After it has been determined that the electrical grid has been built appropriately to minimize larger penetration strains, the load profile for electric vehicles may be forecast. The amount of energy that can be used to power the load on an electric vehicle depends on the battery's capacity [32]. These systems integrate electric vehicles with the grid in a responsive dynamic intelligent electrical network. Then, they transform charging stations into EVs charging stations-for efficacious communication with the user. Their operations include utility providers and an energy management platform too for real-time coordination [33]. With those, everything can be optimized on energy consumption, reduced stress to the grid, and make electricity distribution more reliable and efficient. For example, a smart grid-enabled charger can determine the amount of charging power based on grid conditions, prices calculated for electricity, and preferences used by the user. Technologies like the Internet of Things (IoT), cloud computing, and edge devices serve in most cases to monitor and control the electric flow [34]. It should also be noted that they are much concerned with Vehicle-to-Grid (V2G) technology, through which the electric vehicle will return energy to the grid when needed in addition to consuming it, providing services such as peak shaving and frequency regulation. These systems are important to put in place large-scale EV deployment, especially in cities, where unmanaged charging will lead to voltage instabilities and battery transformer overloads. Smart grid-connected EV charging qualifies end-to-end mobility capability and sustainable grid operation through load forecasting, demand response, and renewable integration, which is consistent with transition goals toward a low-carbon energy economy [35].

AI-enabled smart grids used in EV charging rely on continuous data exchange between vehicles, charging stations, and grid operators to optimize performance, manage loads, and forecast demand. This dependence on real-time data, including user behavior, location, and energy usage, introduces significant cybersecurity and privacy risks. Unauthorized access or manipulation of this data can disrupt grid operations, compromise personal information, and erode public trust in smart charging infrastructure [36]. To address these challenges, robust cybersecurity measures such as encryption, secure communication protocols, and intrusion detection systems are essential. Additionally, privacy-preserving AI techniques—like federated learning and differential privacy—can help minimize the exposure of sensitive user data while still enabling intelligent system control. Ensuring compliance with data protection standards and implementing secure, adaptive frameworks will be key to maintaining both operational resilience and user confidence in AI-driven EV charging networks [37]. Modern EV charging systems include bidirectional power flow-the capability of electric vehicles to both draw energy from the grid for charging and discharge stored energy back to the grid, also referred to as Vehicle-to-Grid (V2G). Together with load management, this two-way exchange transforms EVs into more than just passive loads; V2Gs are active grid resources effectively using EVs for applications such as peak shaving, frequency regulation, and emergency backup. For instance, electric vehicles discharge power back to the grid during peak electricity demand, displacing some amount of required generation. Conversely, during times of less demand and high surpluses of renewable generation, electric vehicles can charge much more beneficially and effectively [38].

Dynamic load management form part of this feature which is the capability of adjusting the EV's charging rate depending on the present condition of the grid, availability of renewable energy, and user preferences. Consequently, it displaces loads intelligently over time and across chargers, preventing transformer overloading and reducing peak demand and optimizing the amount of energy available. Such AI algorithms and IoT-based communication systems would play a tremendous role in facilitating this flexible operation, enabling the system to react in real-time to changes in supply and demand. Bidirectional power flow, in combination with dynamic load management, improves resilience in grids, makes energy use efficient, and enables the penetration of renewables into the transportation energy ecosystem [39].

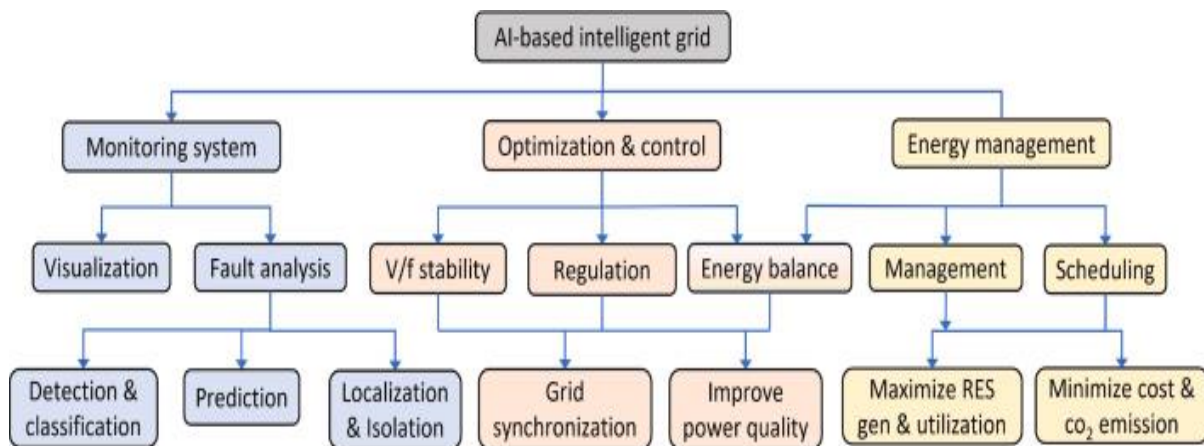


Fig. 3. Important AI-based smart grid system [40].

In figure 3, the different parts of an AI-based intelligent grid system are hierarchical in design. They include monitoring systems, optimization and control, and finally energy management systems. Apart from enabling real-time visualization and fault analysis through detection, classification, and fault localization, the monitoring system also caters to predictive maintenance. This is made possible because an optimization and control module maintains good frequency and voltage (V/f) steady-state characteristics, regulation, synchronization of grids, and energy balancing that managerially augments the quality of the power. On the other hand, the energy management component targets efficient operation of the system by maximizing RES use while minimizing cost and CO₂ emissions through intelligent management and scheduling. The whole figure demonstrates how AI works towards improving adaptability, efficiency, and reliability in smart grids by providing a coordinated and data-driven approach.

The rapid rollout of electric vehicles (EVs) presents major challenges to power grids, particularly in terms of voltage fluctuations, peak load demand, and overload of transformers. Grid impact analysis considers how large-scale EV charging affects the stability, reliability, and performance of existing electrical infrastructure. Unregulated or simultaneous charging at high power can especially burden local distribution networks during peak hours and cause voltage sags, increased power losses, and reduced equipment life. In urban areas with high population density or older grids with limited capacity, these problems become especially important [41].

In line with this phenomenon, several mitigation measures have been conceived and applied. AI-backed smart charging algorithms shift charging to off-peak times, flatten load curves, and coordinate charging schedules according to grid capacity and energy pricing. This gridding flexibility is enhanced by V2G, wherein EVs can discharge to the grid during peak demand. Energy storage systems and demand response programs enhance the ability to support grid performance, aided by forecasting loads. At the long-term level, mitigation comprises infrastructure upgrades and the integration of renewable energy so that the transition may be supported rather than terminated by increases in Evs [42].

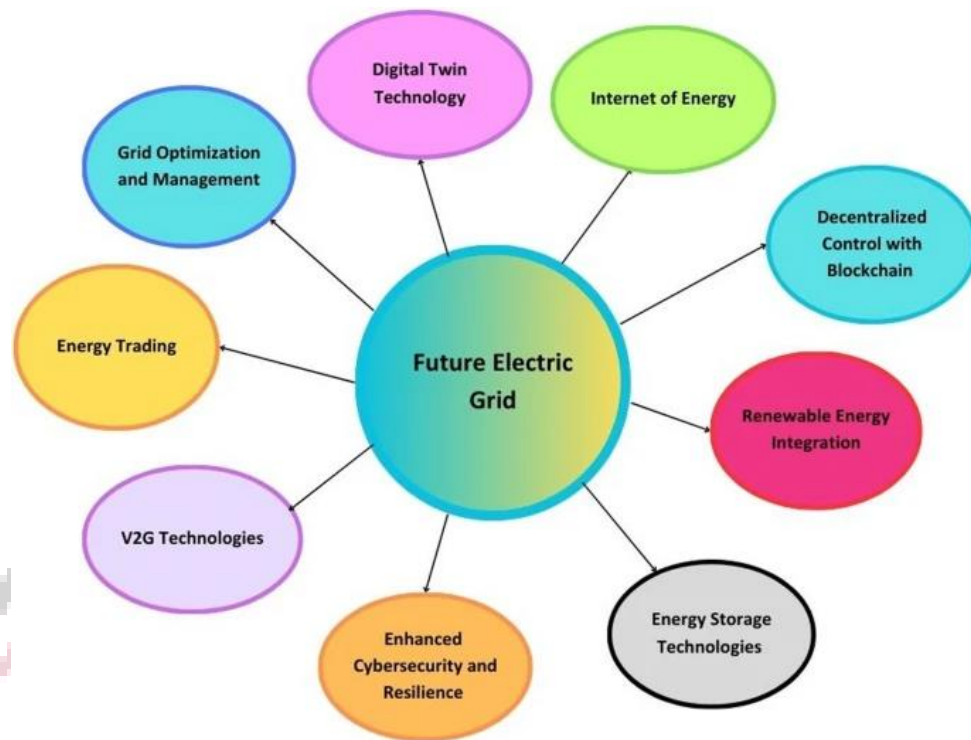


Fig. 4 Key technologies and strategies shaping the future smart grid [43]

Figure 4 illustrates the key technological pillars that will shape the future electric grid, highlighting a shift toward a more decentralized, intelligent, and resilient energy ecosystem. At the core is the integration of advanced concepts such as Digital Twin Technology and the Internet of Energy, which enable real-time monitoring and optimization of grid operations. The figure also emphasizes the role of decentralized control using blockchain, ensuring secure, transparent energy transactions and peer-to-peer trading. Renewable energy integration and energy storage technologies are central to enabling cleaner and more stable energy supply, while V2G (Vehicle-to-Grid) technologies allow EVs to interact dynamically with the grid. Additional components like energy trading platforms, grid optimization tools, and enhanced cybersecurity and resilience ensure that future grids are not only efficient and flexible but also secure against emerging threats. Together, these elements represent the foundation for a smart, sustainable, and user-centric power grid.

V Systemic Challenges, and Future Research Directions

New technologies have made their way into electric vehicle charging systems that apply artificial intelligence (AI) in conjunction with renewables; however, there are yet striking technical and operational issues to tackle. Most AI load forecasting and energy management models for EV charging are developed using ideal conditions and do not cope well with real-world complexities, such as various driving patterns, fluctuating grid conditions, and inconsistent renewable output. Another recurring issue is interoperability-integration of communication and control systems among electric vehicles, their charging stations, and renewable sources is rarely constructed upon common standards, resulting in fragmented performance of the system as a whole. Most of these solutions are made to optimize just one parameter, say, cost or efficiency in energy use, rather than looking at several often-conflicting objectives, including grid stability, emissions, and user convenience. Future developments in AI will further transform smart charging infrastructure [44]. Newly emerging paradigms like deep reinforcement learning and federated learning will allow real-time adaptation of EV charging systems while preserving the privacy of user data. Such advanced paradigms are paving the way for decentralization and self-governing networks in which vehicles, energy storage systems, and distributed generation can interact in ways previously coordinated through centralized oversight. The evolution of such infrastructure entails the provision of community microgrids, peer-to-peer energy transactions, and consumer-centric charging systems, which are indicative of the sustainable and smart approach to urban development [45].

Yet the progress happens rapidly, but policy and regulatory frameworks concerning these advancements have not kept pace with the advancements. They have created hurdles, especially since existing protocols were not unified on the communication, V2G integration, and energy data handling standards, as well as existing policy gaps in

the fields of data privacy and cybersecurity. Systems are left susceptible to misuse and exploitation under these conditions. Without clear legal stipulations, the mass uptake of AI-dependent technology would be stifled, causing delays in the wider systems changeover. To ensure that systems are safe, fair, and sustainable, regulatory progress must be tied with technological advancement. For this, future studies must go beyond integrated research to multidisciplinary collaboration. It is necessary for experts in the areas of artificial intelligence, power systems, transportation planning, cybersecurity, and environmental policy to work together to resolve problems relating to scalability, grid resilience, ethical data use, and access by users. Application research may further include implementation of solutions in areas that are densely packed as well as underserved such that the deployment of EV infrastructure contributes to equity and climate objectives. Priority setting should mainly be about flexible, adaptable, and also inclusive solutions [46].

VI Conclusion

Charging systems for electric vehicles that use artificial intelligence and renewable energy will pave the way for a clean, smart, and resilient energy future. Technically and regulatory-wise, AI combined with intelligent control, sustainable sources of energy, and interaction with the grid is allowing for charging ecosystems that favor efficiency and people. Advancements in AI optimization, demand forecasting, and energy management are helping make the EV ecosystem much more flexible, scalable, and aligned with decarbonization goals. A continuous flow of innovations along with policy support and cross-sector collaboration will be instrumental in realizing the smart EV charging systems to their full potential. In summary, the merging of these technologies signifies a propellant toward sustainable mobility and smarter cities.

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