

Challenges, Strategies and Optimization Techniques for Solar Powered EV Charging Station

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Abstract: Electric vehicles (EVs) are increasingly popular as a dependable alternative to gas-powered vehicles. These vehicles rely on batteries for operation. Despite the long-standing prevalence of grid-based EV charging, solar-powered EV chargers are emerging as an intriguing alternative. By supplying clean electricity to electric vehicles, which produce no pollution of their own, these chargers play a significant role in environmental conservation. The escalating demand for sustainable energy solutions and the growing appeal of electric vehicles have driven the development of innovative charging infrastructure. This paper aims to pioneer the development and construction of an advanced solarpowered electric vehicle charging station. The primary aim of the station is to charge electric cars using solar energy, providing a cost-effective and environmentally friendly option. The integration of solar panels, energy storage systems, charging infrastructure design, and smart grid connectivity are among the critical components of this project. The program seeks to merge electric car technology with renewable energy sources to contribute to eco-friendlier and sustainable transportation ecosystem.

Keywords: EV charging stations, BESS, solar PV system

I. INTRODUCTION

The use of electric vehicles (EVs) as a dependable substitute for conventional gas-powered automobiles is growing in popularity. Batteries power these vehicles. Solarpowered EV chargers are becoming more and more popular, even though grid-based EV charging has long been the standard. Because EVs don't emit any

pollutants, these chargers help to preserve the environment by giving EVs access to clean electricity. The creation of creative charging infrastructure has been fueled by the growing need for renewable energy sources and the allure of electric cars. The goal of this project is to set the standard for building cutting edge solar-powered charging stations for electric vehicles. Its primary goal is to charge electric cars using solar energy, offering a cost-effective and environmentally friendly option. Key components of this project include the integration of solar panels, energy storage systems, charging infrastructure design, and smart grid connectivity. The program seeks to combine electric vehicle technology with renewable energy sources to foster a eco-friendlier and sustainable transportation ecosystem. The project's abstract underscores its significance in tackling pressing issues related to energy sustainability and reducing the transportation sector's carbon footprint.

The worldwide transition toward low-carbon energy and sustainable transportation—driven by global climate initiatives such as the Paris Agreement—has significantly boosted the uptake of electric vehicles (EVs) and renewable energy sources (RESs).

A distinctive contribution of this work is its integrated framework that brings together technical, economic, environmental, and regulatory dimensions, while also developing a structured classification that connects energy management strategies, optimization methods, and policy considerations into a cohesive planning approach. The study categorizes the primary obstacles into four groups: technical issues, economic and infrastructure limitations, environmental concerns, and planning or regulatory challenges.[1]

In addition, various EV charging methods are examined—including vehicle-to-grid (V2G), grid-to-vehicle (G2V), wireless inductive charging, battery swapping, and smart charging—to evaluate their effects on load patterns and grid performance. To support the dependable and adaptable integration of EVCSs and RESs, the chapter also reviews advanced energy management approaches such as demand response mechanisms, aggregator-led distributed control, and hierarchical control systems.



Fig.1. Various effects of EV charging on grid.

The importance of multi-objective optimization is emphasized in addressing trade-offs between conflicting goals like cost minimization, emission reduction, voltage stability, and user acceptance. Furthermore, a range of decision-support tools is discussed for determining the optimal placement, capacity, and operation of EVCS and renewable infrastructure. Overall, the chapter offers a comprehensive and organized overview of current research and real-world developments, providing valuable guidance for policymakers, utilities, and researchers in shaping future energy strategies and investment decisions.

Over the last decade, rising awareness of climate change, air pollution, and greenhouse gas (GHG) emissions has significantly influenced global energy and transportation strategies. In response, electric vehicles (EVs) have emerged as a central component in the shift toward cleaner mobility. Their increasing adoption has been driven not only by environmental goals but also by strong governmental policies promoting low-emission transportation. A dependable and widespread charging infrastructure is crucial to maintain this momentum.

However, large-scale electrification of transport presents considerable challenges for existing power systems, which were not originally designed to handle the substantial demand associated with extensive EV charging. International efforts, including the Paris

Agreement (COP21) and subsequent climate conferences, have encouraged nations to decarbonize both transportation and energy sectors. Consequently, governments and private stakeholders worldwide are making significant investments in the development of electric vehicle charging stations (EVCSs) to improve accessibility and support wider adoption.

Practical initiatives have further accelerated this transition. For example, projects such as Electric Nation and Electric Avenue in the United Kingdom have generated valuable real-world data for analyzing EV charging behavior and its impact on power networks. Similarly, the Sciurus Project has demonstrated the technical and economic feasibility of vehicle-to-grid (V2G) operations, highlighting their potential to support grid stability and manage peak demand. In the Netherlands, coordinated smart-charging programs have shown that aligning EV charging with renewable energy generation can enhance system flexibility and lower emissions.

The integration of renewable energy sources (RESs), particularly solar and wind, into EV charging infrastructure offers a promising way to reduce the carbon footprint of charging while improving long-term sustainability. Nevertheless, the intermittent nature of these energy sources introduces operational challenges, including voltage fluctuations, frequency deviations, and increased losses in active distribution networks (ADNs). To address these issues, careful planning of EVCS placement, capacity, and reactive power support is essential to maintain stable voltage levels, minimize losses, and ensure reliable system performance.[2]

In addition to traditional grid-connected charging, emerging technologies such as plug-in hybrid electric vehicles and electric road systems (ERS)—which enable dynamic charging of vehicles while in motion—are gaining attention as complementary solutions. Although ERS is still at an early stage of deployment in regions like Europe and China, initial studies indicate that combining such systems with conventional depot-based charging could offer cost-effective benefits during the early phases of EV fleet expansion.

II. TECHNICAL CHALLENGES

The simultaneous operation of DGs and EVCSs presents interesting technical challenges, especially when EV charging is uncoordinated or unscheduled. These challenges stem largely from the chaotic patterns of load, the uncertainty presented by renewable-based resources, and the free-for-all charging behavior of EVs.

These issues are primarily due to the rising demand for real-time power, unbalanced loading, and voltage level fluctuations along the distribution network.

Voltage profile deviation and regulation issues: At certain times, such as peak periods of charging and/or when solar output is reduced, rapid swings in voltage levels may occur throughout the network. The result is voltage sags or swells that exceed the acceptable limit, which can affect the quality of the power and the performance of end-user equipment [8]. The term ‘duck curve’ originates from California’s experience with large-scale solar PV integration, where midday over-generation followed by steep evening demand ramps revealed new operational challenges. This pattern is now commonly used to show net-load ramps in modern grids.

Grid congestion and equipment overloads: With the fast and simultaneous charging of EVs at fast-charging stations, a concentrated and sudden burden is placed on the distribution grid. When this aggregated demand exceeds the thermal loading limits or rated capacity of grid components, such as distribution transformers, feeders, or substations, they become overloaded. This not only leads to increased asset ageing due to thermal stresses but also shortens the equipment’s life expectancy and increases the probability of local outages or grid insecurity.[3]

Power quality impairment: Harmonic distortions caused by power-electronic converters in EV chargers remain a growing concern. Most harmonics are produced by nonlinear consumer loads, with the dominant being the EV chargers. At the same time, renewable energy generating units exhibit stochastic behavior that contributes to voltage flickers, frequency deviations, and transients. These power quality issues can interfere with the operation of voltage-sensitive industrial equipment, potentially causing the tripping of protective devices. This makes compliance with grid standards, such as IEEE 519, more challenging. However, battery energy storage, flexible demand response, and coordinated EV smart charging are all examples of mitigation measures that can help smooth out these variations and lower the stress on voltage regulation. Moreover, active filters and advanced converter topologies are being developed to suppress harmonics and improve power quality. These forward-looking strategies show that the problems with integrating EVs and renewable energy can be resolved by incorporating new technological evolution and coordinated operation.

2.2 Economic and infrastructure-related constraints

One of the most significant barriers to the development of EVCS and REG integration is their economic viability. Savings in the long run are commonly referred to as one of the advantages of renewables and EVs; however, a high amount of investment is required to overcome these hurdles.

Costly installation and grid reinforcement: The costs of EV charging infrastructure vary significantly with charger type and location. For example, Level 2 chargers typically cost several hundred dollars per kW installed, while DC fast-charging stations can exceed several thousand dollars per kW, particularly in urban areas where grid reinforcement is often necessary. Moreover, if EVCSs are cointegrated into distributed renewable generators, it usually mandates substantial expansion of the current distribution system. Such upgrades can include the augmentation or replacement of transformer banks, feeders, voltage regulation, and protection relays to support higher loads and bidirectional power flows. These upgrades are a major investment involving material, financial, and operational concerns for utilities and distribution network operators.

Operational and maintenance (O&M) costs: Reliable operation of DG units and EVCSs requires ongoing investment in highly trained personnel, advanced diagnostics, remote monitoring systems, and preventive maintenance plans. The difficulty in managing distributed resources and ensuring service availability under various load profiles results in significant O&M costs, especially in smart grid scenarios where a high level of automation and data exchange is required. Moreover, the costs associated with O&M are substantial, yet digitalization and predictive maintenance tools, including AI-based monitoring, are increasingly reducing long-term expenses.

Tariff design challenges: Traditional pricing structures, such as fixed and flat pricing, are not dynamic, do not reflect real-time grid conditions, and hardly motivate demand-side flexibility, especially for EV charging. Dynamic pricing, combined with smart-charging technologies, has demonstrated measurable success in shifting EV loads away from peak periods in real-world pilot projects, underscoring the potential of economic incentives to enhance grid flexibility. Moreover, consumers’ low level of interest in their load profiles and participation in peak demand results in inefficiencies not only on the consumer side but also on the utility’s supply side, causing an increase in operational costs for the utility.

2.3 Environmental constraints

Integrating EVs and REG is heavily promoted as a crucial step in decarbonization. Although the principle of combining EVs with renewables is mostly environmentally driven, there are paradoxical implications when poorly implemented. These issues underscore the need for an integrated, whole-system perspective.

GHG emissions related to the dependence on grid: In power systems that remain heavily reliant on fossil fuel-based generation, the large-scale electrification of transportation through EVs may represent a spatial redistribution rather than an actual reduction of emissions, shifting them from vehicle tailpipes to centralised power plants. Under such circumstances, the additional charging demand from EVs can increase the operational load on thermal generation units, especially during peak periods when renewable energy output is limited. Consequently, the overall GHG mitigation potential of EV deployment is constrained by the extent of renewable energy penetration, thereby raising concerns about the genuine net environmental benefits of such environmentally motivated transitions.[4]

Sustainability compliance and life cycle considerations: EV and renewable integration, as environmental sustainability, does not only focus on short-term emission reduction. To align with holistic sustainability frameworks, most notably the United Nations' sustainable development goals, a full life cycle assessment approach is required. This considers the environmental impacts throughout the entire life cycle, from the extraction of raw materials to manufacturing, use, and recycling.

2.4 Planning and regulation gaps

Policy and regulatory gaps, along with a disjointed institutional framework, continue to make the integration between EVCS and REG more challenging. Uncoordinated planning can lead to inefficient investments in infrastructure, inconsistent technical standards, and missed chances to work together. To sum up, the main gaps are as follows:

Nonexistent grid codes/standards: The lack of uniform grid codes and harmonised engineering standards is a major barrier to the seamless integration of EVCS and REG. Variations at the regional level and among manufacturers create interoperability challenges, disrupt protection coordination, and result in inconsistent operational procedures. For instance, while standards such as IEEE 1547 and IEC 61850 establish

key requirements for grid-connected distributed resources, their implementation remains incomplete or inconsistent across regions. This absence of alignment complicates system planning, restricts scalability, and increases reliability concerns for both utilities and EV infrastructure.

Insufficient long-term planning of infrastructure: The lack of integrated, data-driven long-term planning often results in overbuilt or underutilised infrastructure, uneconomic capital deployment, and suboptimal grid operation.

Underdeveloped mechanisms to coordinate charging: The absence of effective policy and regulatory instruments limits the implementation of multi-level coordinated charging (aggregator, user, grid), demand response programs, and fleet-based incentive schemes. Even though there are well-known technical solutions for coordinated charging, their utilization in real life is constrained by incentive systems and a lack of regulatory support.

EV Charging Strategies

With electric vehicles (EVs) expected to dominate future personal and commercial transport, their integration into active distribution networks (ADNs) calls for more advanced and coordinated charging approaches.

III. EV CHARGING TECHNIQUES

3.1 Wireless and Inductive Charging Techniques

Wireless, or inductive, charging is an emerging technology that enables energy transfer without a physical connection between the vehicle and the power supply. It operates on the principle of electromagnetic induction: a primary coil—typically embedded in the ground—generates an alternating magnetic field, which is captured by a secondary coil installed in the vehicle. Energy is then transferred through magnetic coupling, often enhanced by resonance techniques. This contactless method improves user convenience and enables automation, making it particularly suitable for urban environments, autonomous systems, and high-utilisation vehicle fleets.

3.1.1 Static Inductive Charging (SIC)

Static inductive charging takes place when the vehicle is parked, such as in residential garages, parking areas, or designated public charging spaces. It offers benefits like enhanced safety, ease of use, and minimal manual intervention. However, compared to conventional plug-in charging, SIC systems generally experience lower efficiency, mainly due to coil misalignment and

increased electromagnetic losses. Common applications include home charging setups, inductive charging pads, and fleet depots.

Despite its advantages, SIC faces several technical and economic challenges. Power transfer efficiency can be reduced by factors such as improper alignment between coils, larger air gaps, and leakage of the magnetic field. These issues often lead to higher energy losses than those observed in conductive charging systems. Additionally, deploying SIC infrastructure requires substantial upfront investment, as it involves installing underground coils, power electronic converters, and control systems. This contributes to a higher overall cost of implementation.[5]

3.1.2 Dynamic inductive charging (DIC)

Dynamic inductive charging enables EVs to charge while in motion by drawing power from coils embedded within the roadway surface, as illustrated in Figure 3. These coils, which are activated consecutively, send energy wirelessly to the car as it moves, so the battery does not need to be recharged partially or fully [18]. If widespread use of this technology occurs, it might transform electric transportation by reducing the need for large batteries. This would make automobiles more compact and economical, while also addressing range concerns. Despite its potential, the large-scale deployment of DIC in mainstream transportation systems remains constrained by several critical factors. These include substantial infrastructure investments for road reconstruction or retrofitting, complex standardization and interoperability requirements, and the need to address potential electromagnetic exposure and safety compliance [19]. Successful integration of DIC within existing transportation and power-grid frameworks requires full coordination among stakeholders, such as utility operators, transport authorities, and regulators.[6]

3.1.3 Static Conductive Charging (SCC)

Static conductive charging refers to the process of supplying power to an electric vehicle (EV) through a direct electrical connection with the grid using a charging cable while the vehicle is stationary. It is among the most widely adopted and commercially established charging methods. Depending on the system configuration, chargers used in this approach are classified into two types: on-board chargers, which are integrated within the vehicle, and off-board chargers, which are external units that deliver power to the EV.

Figure 4 illustrates the basic working concept of the SCC approach.

3.1.4 Dynamic Conductive Charging (DCC)

Dynamic conductive charging enables electric vehicles (EVs) to draw power from the grid while in motion, eliminating the need to rely solely on stored battery energy. This approach supports continuous energy supply during travel, which can significantly reduce the requirement for large onboard battery capacities.

DCC systems are typically implemented in two main ways. The first involves embedding conductive rails or tracks within the road surface, allowing vehicles to collect power as they move. The second configuration uses an overhead catenary arrangement, where a conductive arm mounted on the vehicle connects to high-voltage lines suspended above the roadway.

This charging method is particularly well-suited for heavy-duty electric vehicles, such as buses and freight trucks, especially those operating along fixed routes. Figure 5 presents a conceptual overview of dynamic conductive charging alongside static inductive charging techniques.

3.2 Battery Swapping (BS) and Fast-Charging Methods

To improve the practicality and user acceptance of electric vehicles (EVs), particularly in commercial and high-demand applications, rapid energy replenishment solutions such as battery swapping and fast charging have been introduced. Both approaches aim to minimise charging delays and reduce vehicle downtime, thereby making EV operation more comparable to conventional internal combustion engine (ICE) vehicles.

3.2.1 Battery Swapping

Battery swapping involves replacing a depleted battery with a fully charged one at a dedicated station, significantly reducing service time to just a few minutes. This makes it especially attractive for applications such as taxis, delivery fleets, and public transportation systems.

Despite its operational benefits, several challenges limit large-scale adoption. These include the lack of standardization in battery design and vehicle interfaces, uncertainties related to battery ownership and responsibility (such as leasing versus ownership models), and the substantial investment required for maintaining battery inventories and automated swapping facilities. Figure 6 illustrates the working concept of the battery swapping system.

3.2.2 Fast Charging

Fast charging enables EV batteries to be recharged in a short time—typically within 20 to 30 minutes—using high-power charging stations, often exceeding 50 kW. This method is particularly valuable along highways, in urban transit hubs, and in commercial settings where quick turnaround times are essential.

However, integrating fast-charging infrastructure into existing distribution networks presents technical challenges. The high and sudden power demand can lead to voltage drops, harmonic issues, and increased thermal stress on electrical equipment. To mitigate these effects, fast-charging stations are often supported by local renewable generation (such as rooftop solar), energy storage systems (ESS), and advanced control

mechanisms. These measures help balance demand fluctuations and maintain grid stability.[7]

IV. ENERGY MANAGEMENT STRATEGIES

As the global energy transition increasingly focuses on decarbonization, decentralization, and digitalization, the interaction among electric vehicles (EVs), renewable energy generation (REG), and active distribution networks (ADNs) has become more intricate and significant. This combination of mobile energy users and providers, fluctuating renewable inputs, and actively managed grid systems necessitates the development of advanced, real-time energy management systems (EMSs). Such systems must ensure reliable operation, cost-effectiveness, and environmental sustainability at the same time.

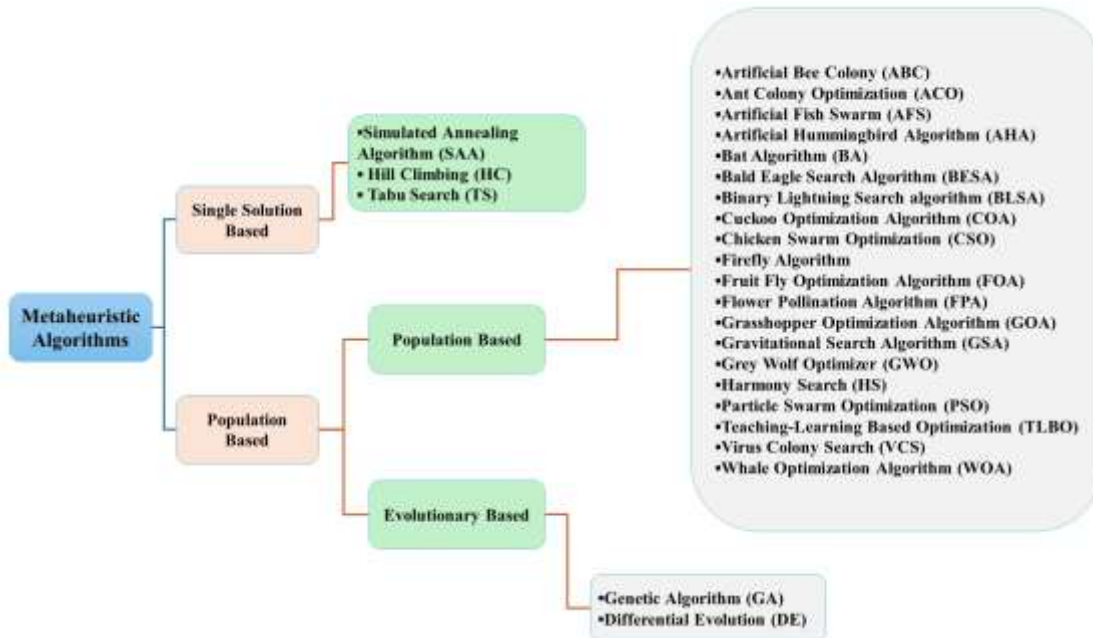


Fig.2. Metaheuristic Techniques applied for EV Charging

4.1 Demand Response (DR) Integration Framework

Demand response has emerged as a fundamental component of modern smart grid systems. In the context of integrating EVs and renewable energy into ADNs, DR plays a crucial role in enhancing load flexibility, maintaining system balance, and improving grid resilience.

4.1.1 Incentive-Based Demand Response

In incentive-based DR programs, EV users voluntarily participate in grid-support initiatives in exchange for financial rewards or other benefits. These programs are typically coordinated by utilities or aggregators that manage charging activities under specific conditions.

Direct Load Control: Utilities or aggregators temporarily adjust or suspend EV charging during peak demand periods.

Vehicle-to-Grid (V2G) Incentives: EV owners receive compensation for supplying stored energy back to the grid, supporting services such as frequency regulation and peak load reduction.

Emergency Demand Response: Users are rewarded for reducing or postponing charging during unexpected system stress or supply shortages.

4.2 Load Forecasting Methods

Accurate load forecasting has become essential for efficient grid operation in systems with widespread EV adoption and high penetration of renewable energy. Reliable forecasting tools help

operators anticipate demand peaks, prevent congestion, reduce renewable energy curtailment, and optimize the use of distributed energy resources.

4.2.1 Statistical Time-Series Models

Traditional forecasting approaches are largely based on statistical methods that extend historical demand patterns into the future.

ARIMA (Autoregressive Integrated Moving Average): Widely used for short-term forecasting, ARIMA models capture linear relationships and recurring seasonal patterns in EV charging demand when sufficient historical data is available.

Exponential Smoothing (ES): These techniques assign greater importance to recent observations, making them suitable for systems with evolving trends or sudden changes, such as daily or seasonal variations in EV usage.

4.2.2 Machine Learning-Based Forecasting

Machine learning approaches have gained prominence due to their ability to model complex, nonlinear relationships between multiple influencing factors, such as weather conditions, user behaviour, traffic flow, and electricity prices. These methods typically require large datasets but can uncover patterns without predefined assumptions.

Artificial Neural Networks (ANN): Capable of capturing nonlinear dependencies among inputs and outputs, ANNs are effective for predicting both individual and aggregated EV charging demand.

Support Vector Machines (SVM): Suitable for high-dimensional datasets, SVMs are applied in both regression and classification tasks and perform well under uncertain system conditions.

Random Forest (RF): This ensemble learning method combines multiple decision trees to improve prediction accuracy and robustness. It is particularly useful for handling mixed data types and modelling nonlinear relationships in EV load forecasting.

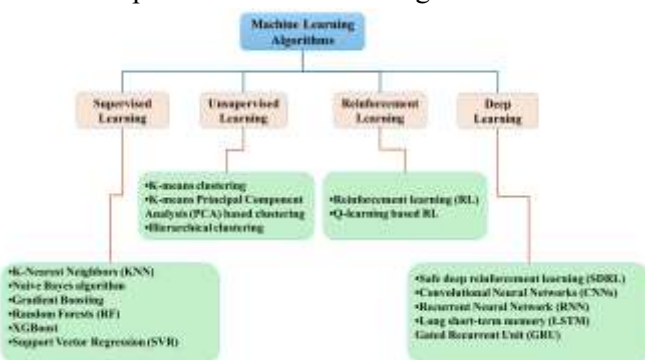


Fig.3. Machine Learning algorithms for EV

V. Optimization Framework and Allocation in Distribution Grids

A variety of optimization approaches have been developed to address the challenges associated with the strategic placement of electric vehicle charging stations (EVCSs) and renewable energy generation (REG) within distribution networks. In a multi-objective setting, these methods evaluate trade-offs among economic, technical, and environmental criteria to identify Pareto-efficient solutions that meet overall system goals while respecting local constraints.

More recently, artificial intelligence (AI) and machine learning-based optimization methods have attracted considerable attention. Their strength lies in managing high-dimensional and time-varying data, which is typical in active distribution network (ADN) planning.

5.1 Multi-Objective Optimization (MOO)

Traditional single-objective optimization models, which focus on only one performance metric, are no longer adequate for modern power systems. The increasing complexity of ADNs requires approaches that can simultaneously address multiple, often conflicting objectives. Multi-objective optimization provides a structured framework to achieve this by analysing trade-offs among competing goals. MOO techniques generate a set of Pareto-optimal solutions, where improving one objective would lead to the deterioration of another. This allows decision-makers to select the most suitable solution based on system priorities and constraints.

5.1.1 Integration of Environmental and Policy Objectives in MOO Models

With increasing global emphasis on carbon neutrality and sustainable resource management, recent research has focused on embedding environmental and policy-related considerations into optimization frameworks. These include factors such as emission reduction targets, carbon pricing schemes, and land-use constraints. One common strategy is to treat greenhouse gas (GHG) emissions as a direct objective within the optimization model, ensuring that environmental impacts are explicitly accounted for during decision-making.

For instance, EV charging schedules can be strategically aligned with periods when electricity is generated from low-carbon sources, thereby reducing the indirect emissions associated with electric mobility. In a similar way, carbon pricing mechanisms or environmental taxes can be incorporated into cost functions, allowing infrastructure planning decisions to reflect broader

decarbonisation goals set by national and international policies.

A widely adopted approach for such integrated planning is the two-stage stochastic mixed-integer linear programming (MILP) model. In this framework, long-term investment decisions—such as the placement and capacity of EVCSs and renewable energy systems—are determined in the first stage. The second stage focuses on operational aspects, including real-time dispatch and system management, while accounting for uncertainties in demand, renewable generation, and pricing or carbon cost variations.

This two-level optimization structure provides a robust foundation for sustainable energy system planning by balancing economic efficiency, regulatory compliance, and system reliability under uncertain conditions. Table 3 presents a comparative review of existing optimization studies, highlighting their methodologies, advantages, and key contributions.

5.1.2 Decision-Making Based on MOO Outcomes

The solution of a multi-objective optimization (MOO) problem typically consists of a set of non-dominated alternatives, often visualized as a Pareto front. Each solution represents a different balance among competing objectives, allowing decision-makers to choose an option that aligns best with their strategic goals or policy priorities.

To support this selection process, multi-criteria decision analysis (MCDA) methods are widely applied. One commonly used technique is the Analytic Hierarchy Process (AHP), which structures decision problems through pairwise comparisons of criteria and aggregates them into an overall ranking. Another approach, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), evaluates alternatives based on their relative distance from an ideal solution, enabling clear and intuitive comparisons.

Fuzzy logic-based methods can handle imprecise or linguistic inputs, making them suitable for complex decision environments.

Overall, such decision-support tools enhance the usability of MOO results by converting technical trade-offs into actionable insights, incorporating both quantitative performance measures and qualitative preferences.

VI. CONCLUSION

The joint planning of renewable energy generation (REG) and electric vehicle charging stations (EVCSs) is critical for developing a distribution network that is

reliable, efficient, and environmentally sustainable. The discussion in this chapter highlights that uncoordinated or rapid deployment of EVCSs and REG can lead to issues such as network stress, voltage fluctuations, and inefficient investment decisions. To overcome these challenges, there is a clear need for integrated, data-driven, and flexible planning approaches.

Multi-objective optimization (MOO) methods play a central role in this context by enabling simultaneous consideration of technical, economic, and environmental factors. These approaches help reduce power losses and voltage variations, optimise capital and operational costs, and minimise greenhouse gas emissions as well as land-use impacts. As a result, they provide a systematic framework for evaluating trade-offs and support the development of sustainable, cost-effective, and grid-compatible infrastructure.

Furthermore, the successful integration of EVs and renewable energy systems relies on strong policy alignment, effective regulatory frameworks, and increased digitalisation of distribution networks. Technologies such as smart metering, advanced forecasting tools, and adaptive control systems can significantly improve both planning precision and real-time system operation.

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