



# Towards Sustainable Electric Vehicle Charging: A Comprehensive Review of Methods, Energy Sources, Charging Technologies, Converter Configurations, and Various Optimization Strategies

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**Abstract:** The changeover from gasoline or petrol engines to electric vehicles (EVs) is motivated by advanced technologies that enhance EV adoption, efficiency, and accessibility. EVs address key challenges by reducing carbon emissions and dependence on fossil fuels. Some key factors, such as EV sources, EV charging methods, EV technologies, converters used in EVs for battery charging, optimization methods incorporated, battery charging times, and EV prices across different sources, should be reviewed to motivate industrialists, researchers, and investors in EVs. This study provides a comprehensive analysis of EV charging technologies, different EV Charging stations (EVCs), converters, EV charging system structures, and optimization techniques used to improve performance. Renewable energy-based EVCs utilize locally available energy resources to reduce reliance on fossil fuels. Recent advances in power converter topologies improve power quality and enable flexible AC/DC operation. EV charging methods include wireless charging, battery swapping, and pantograph systems. To meet diverse user demands, EV technologies integrate hybrid systems, fuel cells, batteries, and renewable sources. Optimization techniques enable efficient charging/discharging, grid code compliance, optimal charging station placement, coordinated multi-EV charging, and energy management. This study examines the factors influencing EVs and charging infrastructure, the challenges they face, and future directions, emphasizing the need for coordinated efforts by manufacturers, transport agencies, and governments to support sustainable, large-scale EV adoption.

**Keywords:** Electric vehicles; EV charging station; EV technologies; converters; optimization

## 1. Introduction

The exploitation of renewables and electrification may be delayed without adequate time for development; otherwise, this leads to higher CO<sub>2</sub> emissions and higher energy prices for consumers. The oil and gas industry's top brass know that the energy shift is underway. Refiners will be highly dependent on transportation for fuel and oil. Passenger automobiles and trade automobiles are the main contributors to the world's overall carbon footprint [1]. The transition from internal combustion engines to EVs has substantial environmental benefits, particularly in reducing emissions, improving fuel efficiency, and enhancing sustainability [2]. Advances in EV technology, renewable energy integration, and autonomous systems are driving

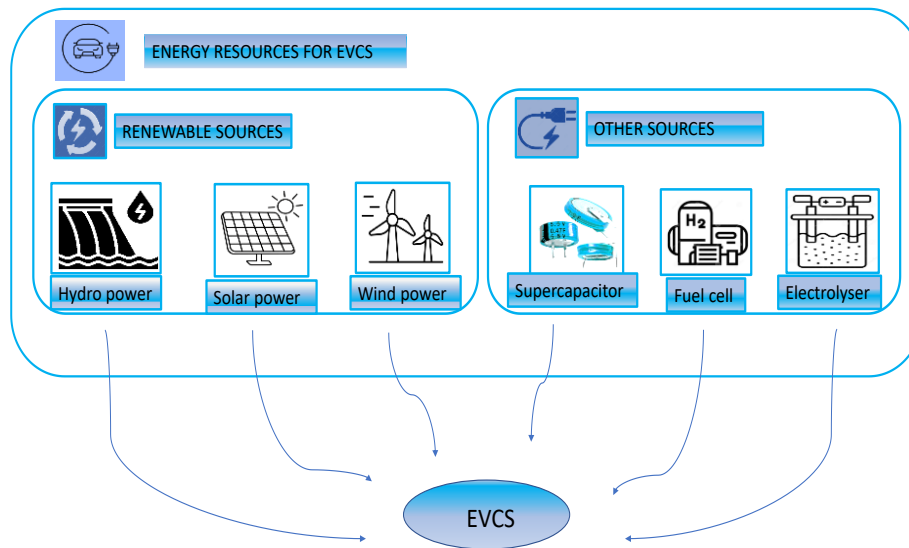
developments in smart grids, energy management, and battery technologies. However, inadequate charging infrastructure can increase grid stress, necessitating power systems that can manage bidirectional power exchange from decentralized renewable sources such as PV and wind energy [3].

New technologies are needed to support rapid EV development, including advanced battery expertise, faster EV adoption, and improved battery designs [4]. V2G technology lets EVs supply power back to the grid when idle, supporting grid stability and generating income for the owner [5]. Fast charging relies on smart, networked infrastructure that integrates EVs with DERs and is supported by software control, GPS, and real-time monitoring to enable efficient bidirectional power flow. To meet the growing needs of EVs, transition to renewable energy, and support the energy-intensive advancement of AI, a clean, robust, and integrated energy network is essential. One challenge with EVs is concerns about battery longevity after charging. Today, various charging connectors, interaction procedures, and pricing have emerged among producers, and charging facility suppliers are also present. This work discusses EV charging methods, EV technology, energy sources integrated into EVCS, converter topologies, and optimization techniques, and provides better guidance for selecting an EV power system.

|              |                                                                 |
|--------------|-----------------------------------------------------------------|
| Section II   | Types of Energy sources and challenges in integration with EVs. |
| Section III  | EV charging and its related control strategies.                 |
| Section IV   | Different current EV charging methods.                          |
| Section V    | EV technologies                                                 |
| Section VI   | Optimized techniques.                                           |
| Section VII  | Future Research Scope.                                          |
| Section VIII | Conclusion                                                      |

## 2. Energy Sources for EV

The incorporation of large numbers of EVs will reshape distribution grid operations and structure. The growing number of electric vehicles on the streets is driving increased demand for EV charging infrastructure [6]. Solar- and wind-powered EV charging reduces greenhouse gas emissions and lowers EV life-cycle impact. Hydro, fuel cell, and biogas systems further support sustainable growth [7]. Figure 1 shows the energy resources used in EVCS. Integrating renewable energy-based DERs with EV systems reduces grid demand and carbon emissions while supporting decarbonization goals. Installing solar and wind systems at EVCSs and commercial facilities further alleviates grid stress and offers economically viable investment opportunities.



**Figure 1.** Energy resources for EVCS

### 2.1 Solar PV-powered EV

Solar-powered EVCSs are flexible and scalable for urban, remote, and off-grid use. Excess solar energy can be stored in EV batteries during peak generation, while smart energy management systems optimize charging by aligning it with periods of high solar availability. Combined with energy storage systems, solar panels enable EVCSs to operate independently as off-grid solutions [8]. Synchronization control between the PV (photovoltaic) system and the BESS is required to sustain power equilibrium [9]. Integrating low-cost robotic technologies into the maintenance routines of solar PV systems, specifically in regions prone to high dust levels, enhances the overall consistency and performance of solar PV power installations [10]. Rooftop solar installations on commercial buildings and car parks are increasingly used to directly control EVCSs in some countries with targets for sustainable energy performance [11].

### 2.2 Wind energy-powered EV

Wind power is vital for EV infrastructure, especially in regions with consistent wind resources. Both onshore and offshore wind farms can generate large amounts of clean electricity, which can be integrated with EV charging networks. Integrating EVs into power systems, with wind influence, is well-suited to establishing supplementary facilities. In some countries, wind energy contributes meaningfully to regulating EV charging hubs along main highways, and integrating wind energy with smart grids allows real-time adjustments to ensure optimal EV charging without overburdening the grid [12]. The scalability of wind energy makes it a model for large-scale backup EV charging, with supercharging networks for a wide variety of EVs.

### 2.3 Hydropower in EV setup

Countries with ample water resources have harnessed hydropower to address EV energy challenges efficiently. Hydropower plants provide a constant energy output, making them ideal for baseload EVCSs. In countries like Norway, where nearly 100% of energy comes from hydropower, EVs are almost entirely powered by renewable sources. Additional sources, such as fuel cells, electrolyzers, and supercapacitors, are used to maintain an EV-centered focus on availability and accessibility [13].

### 2.4 Energy management and challenges in incorporating renewable energy into EV charging stations

Smart charging is the intelligent, data-driven management of EV charging that fully integrates RE resources into EV stations [14]. It uses sophisticated technologies, real-time data, and statistical analytics to optimize EV charging. Smart, data-driven charging systems optimize EV charging by considering renewable availability, grid demand, electricity prices, and user preferences. Using real-time monitoring and analytics, they ensure EVs charge with clean energy whenever possible, reducing carbon emissions and easing grid

stress during peak hours. An EV can serve as an adaptable load or storage resource, with its battery charging and discharging capabilities feeding power to the grid and supporting the V2G concept economically [15]. The growth of wind and solar PV increases grid instability due to their intermittent output, making energy storage systems—particularly lithium-ion batteries—essential for storing excess energy and ensuring reliable EV charging. However, shifting existing EV charging infrastructure to renewable sources requires significant investment [16]. Despite these challenges, advances in energy storage and grid management are gradually addressing them, paving the way for cleaner and more consistent EV arrangements [17]. Table I shows the energy sources used in EVCS and their different modes of operation.

**Table 1.** Energy sources used in EVCS

| Ref No. | Solar PV | Windmill | BESS | Islanded/Grid connected | Other sources              | AC bus/DC bus | THD/Metrics                            | Year |
|---------|----------|----------|------|-------------------------|----------------------------|---------------|----------------------------------------|------|
| [18]    | ✓        | ×        | ✓    | both                    | ×                          | DC bus        | Performance efficiency of 68.90%.      | 2024 |
| [19]    | ×        | ×        | ✓    | Islanded                | Super capacitor            | DC bus        |                                        | 2024 |
| [20]    | ✓        | ✓        | ×    | Grid connected          | Diesel generator           | AC bus        |                                        | 2024 |
| [21]    | ✓        | ×        | ✓    | Grid connected          | Fuel cell                  | DC bus        | 2.159%                                 | 2023 |
| [22]    | ×        | ×        | ×    | Grid connected          | ×                          | AC bus/DC bus |                                        | 2020 |
| [23]    | ✓        | ×        | ✓    | Islanded                | ×                          | DC            | Cost effective                         | 2024 |
| [24]    | ✓        | ×        | ×    | both                    | ×                          | DC bus        | 2.88%                                  | 2021 |
| [25]    | ✓        | ×        | ×    | both                    | ×                          | AC /DC bus    |                                        | 2023 |
| [26]    | ✓        | ✓        | ×    | islanded                | Electrolyzer and fuel cell | ×             |                                        | 2023 |
| [27]    | ✓        | ×        | ✓    | both                    | ×                          | DC bus        | <5%                                    | 2021 |
| [28]    | ✓        | ×        | ✓    | both                    | ×                          | DC bus/AC bus | Standalone-3.83%; Grid-connected-1.54% | 2018 |
| [29]    | ✓        | ×        | ✓    | both                    | ×                          | DC bus        |                                        | 2025 |
| [30]    | ✓        | ×        | ✓    | both                    | Diesel Generator           | DC bus/AC bus | <5%                                    | 2024 |
| [31]    | ✓        | ✓        | ✓    | Islanded                | Fuel cell                  | AC /DC bus    | Renewable Energy Fraction is 97.95%    | 2024 |
| [32]    | ✓        | ✓        | ×    | Grid connected          | Fuel cell                  | AC bus/DC bus |                                        | 2025 |

✓ - used    × - Not used

From Table 1 above, the following statements are suggested.

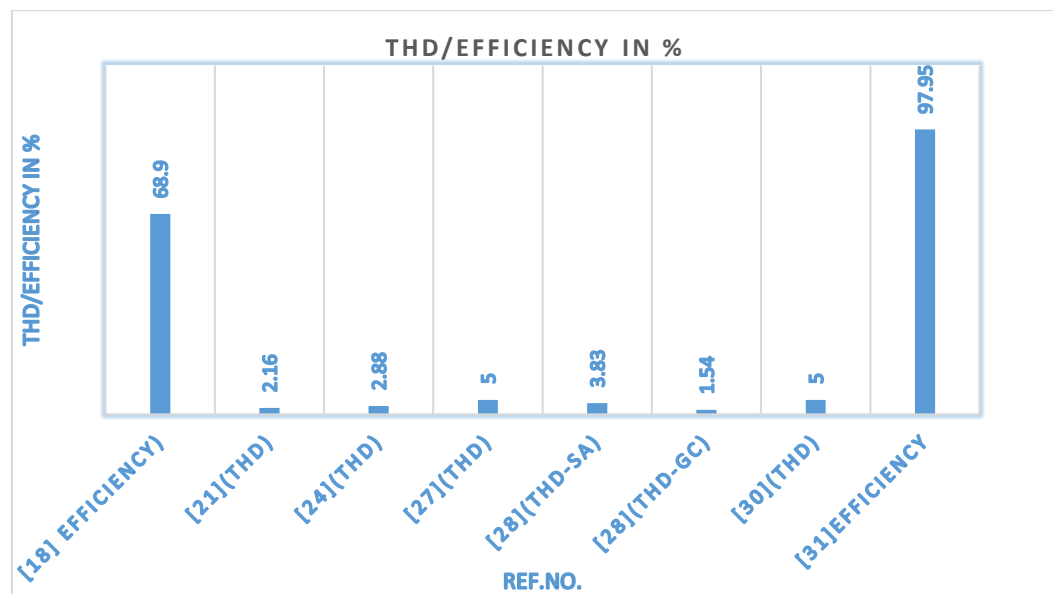
➤ Solar energy is the primary source for EV charging due to its wide availability, followed by wind and hydropower, which can serve as supplementary and base-load sources. Emerging technologies such as fuel cells, supercapacitors, and electrolyzers remain in development. Distributed energy systems may integrate multiple renewable sources with grid and DG support to ensure reliable EV operation during periods of renewable intermittency. Battery energy storage systems are essential for enhancing reliability and preventing supply interruptions, with appropriate sizing of DG, storage, and grid support based on a local renewable resource assessment for EVCS deployment.

➤ Studies indicate that solar PV combined with battery energy storage provides a reliable, cost-effective, and uninterrupted standalone power supply for EVs in regions with high solar irradiance. PV-based charging stations also help reduce grid loading and lower operational costs. When solar and battery resources are insufficient, grid and DG systems help meet EV demand. Without solar input, BES supplies power for charging, reducing grid dependence while exporting excess energy to the grid. Solar-fed EV systems with battery storage can operate in standalone or grid-connected modes [33-37]. Standalone systems use PV and batteries for charging, while grid-connected systems ensure sinusoidal currents to maintain power quality and avoid grid disturbances.

➤ Reliability and financial feasibility are key considerations in designing PV-powered EVCSs. Studies show that integrating BESS improves cost-effectiveness, particularly at higher reliability levels and in islanded (off-grid) operation.

The best approach to EV charging in major areas is grid-centered renewable energy substations. PV-based charging stations with BES have improved power quality for the following reasons.

- Possible to control EVCS in numerous dynamic situations.
- A novel method can be introduced to retain surplus power in the hybrid charging station, switch the energy levels in the energy storage system, and achieve a financial advantage by offering energy to the local grid.
- The grid-connected hybrid system is desired because it reduces the impact of irregularity, as repeatedly monitored through the use of renewable sources.

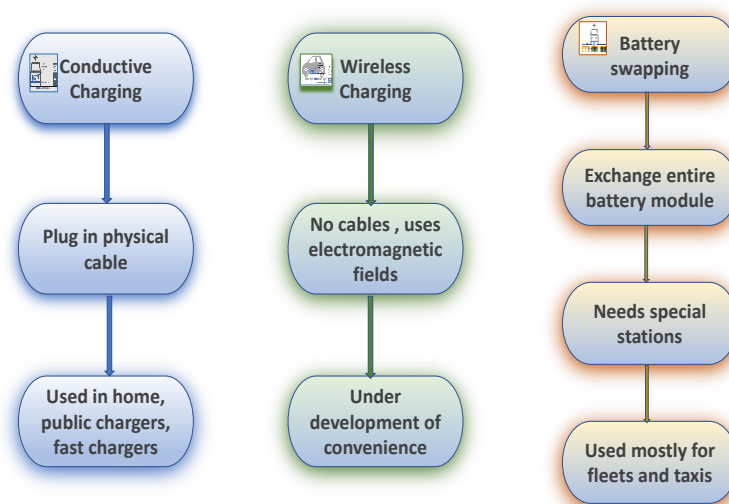


**Figure 2.** Comparison of THD/Efficiency in Energy Sources of EVCS

Figure 2, derived from Table 1, indicates that grid-connected RES achieves superior power quality, with THD values below 2%. In contrast, islanded systems demonstrate higher efficiency and enable more effective use of available renewable energy. Several important aspects are not included in the research, such as other renewable energy sources, energy management and optimization strategies, smart grid interactions, economic and environmental analyses, reliability under varying conditions, and infrastructure and policy considerations. Future work will be extended to support their effective integration and practical implementation.

### 3. EV charging methods

These are broadly classified into conductive charging, wireless charging, and battery swapping station (BSS) methods. Figure 3 shows the different EV-charging methods available.



**Figure 3.** EV charging methods

This section discusses EV charging methods. This section discusses the decisions and recommendations under the strongest circumstances and emphasizes future research directions.

#### 3.1. Conductive charging

EV charging systems are classified as onboard (AC) and offboard (DC) chargers and further categorized by charging speed as Level 1, Level 2, and Level 3. Level 1 charging is slow, typically adding 3.5–6.5 miles of range per hour, and is mainly used as an alternative or backup option. Level 2 chargers operate at 220–240 V and can fully charge an EV with a 300-mile range in approximately 6–8 hours, making them suitable for domestic and commercial applications. Level-3 charging, also known as DC fast or rapid charging, delivers high power and is ideal for locations such as highways, gas stations, and rest stops where quick charging is required.

For rapid charging, the onboard charger can be bypassed, and the energy does not reduce its charging capacity. The onboard charger is suitable for light Plug-in EVs with a small, economical charging system. EV charging occurs via an AC bus supplied by the Grid/DG or by converted AC power from renewable energy sources. Integrating EVs and Energy Storage Systems (ESS) with Renewable Energy Resources (RERs) can mitigate the irregular fluctuations in the electrical power produced by RERs. However, installing charging stations often requires significant investment. If a DC charging station is used and the EV is treated as an ESS, this results in Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) transitions, enabling an economically efficient system. Onboard charging is used when the DG/grid is connected. Offboard charging is used when connected to solar PV/energy storage. If, at a time, the AC and DC ports are used in an EV, it can be charged using the AC grid/DG for the AC port and solar PV/wind/hydro power for the DC port. Off-board EV charging enables fast charging and fast dynamic response. In a grid-connected EVCS, if the grid fails to synchronize, the DC CS

operates autonomously, and the solar PV source also controls the EV battery. Charger selection depends on factors such as potential needs, charging frequency, economic considerations, and whether portability or fast charging is important.

### 3.2 Wireless charging

In wireless EV charging, the primary coil is placed on the road surface, and the secondary coil is mounted in the vehicle. Charging occurs when the vehicle is parked above the system, enabling high-frequency power transfer. Wireless charging is classified into near-field, medium-field, and far-field methods, including inductive, resonant, capacitive, magnetic gear, and emerging microwave, radio-wave, and laser-based techniques. Wireless inductive and capacitive power transfer is less efficient than wired networks. A hybrid wireless power transfer system improves efficiency and reduces current stress by employing S-LCC/SP compensation with constant-current and constant-voltage control for PV-based EV charging. In dynamic wireless charging methods, EVs are in motion, and the mounted power track beneath the lane poses a substantial concern for financial feasibility. Wireless charging is suitable for locations such as taxi stands and bus stations, where vehicles often wait for passengers.

### 3.3 Battery Swapping Station

Battery swapping allows EVs to quickly replace depleted batteries with fully charged ones, avoiding the need to wait for recharging. Combined charging and swapping stations help reduce the impact of e-mobility on the power grid [38]. BSS can play a key role in accelerating EV adoption by offering a faster, more consistent, and environmentally friendly alternative. One paper presents an optimization framework for organizing a battery-swapping station to improve efficiency and sustainability in EV infrastructure [39]. Several studies have examined BSS operations, addressing charging scheduling, facility policies, system architecture, communication and control, and power system integration. These works consider perspectives such as BSS types, decision-making strategies, EV categories, battery standardization, V2G capability, clustering, and operational models [40]. Key challenges in future EV systems include optimal battery sizing, system configuration, high BSS investment costs, and battery protection. Integrating optimized charging strategies with PV systems can reduce energy costs by up to 27.63%. Improved battery-swapping schemes further minimize operating costs and enhance usability at electric bus battery-swapping stations [41]. Another study proposes a framework for optimally placing BSS in smart microgrids with distributed energy resources, considering reliability, power quality, and economic factors, including production and operational costs [42].

BSS shows promise as an effective EV charging solution, but challenges such as stability, interoperability, and user acceptance remain. Research insights guide policymakers, industry, and researchers in developing and implementing BSS. Table 2 reviews different EV charging methods and their remarks.

**Table 2.** EV charging methods

| Ref. | Year | Conductive charging (onboard / offboard) | Wireless charging | Battery swapping | Remarks and suggestions                                                                                              | Metrics                                                          |
|------|------|------------------------------------------|-------------------|------------------|----------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------|
| [35] | 2021 | Offboard/onboard                         | ×                 | ×                | This system supports both AC and DC charging using solar PV or grid power. The CAPSA algorithm optimizes EV current. | Standalone EV power- 2.01kW<br>Grid connected EV power - 2.359kW |

**Table 2.** EV charging methods (continue)

| Ref. | Year | Conductive charging (onboard / offboard) | Wireless charging | Battery swapping  | Remarks and suggestions                                                                                                                                                                                                               | Metrics                                                                                     |
|------|------|------------------------------------------|-------------------|-------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| [36] | 2022 | Onboard                                  | ×                 | ×                 | With an intelligent control management system, optimum EVCS operation is attained.                                                                                                                                                    | Optimized battery SOC between 0.3 and 1.                                                    |
| [43] | 2024 | ✓                                        | ✓                 | ×                 | Compared with wired power transmission, standard Wireless power transfer designs typically have lower transfer efficiency but offer greater adaptability.                                                                             | Transfer efficiency can reach 98% for a given coupling coefficient.                         |
| [44] | 2023 | Offboard                                 | ×                 | ×                 | With supervisory control and a Z-source converter, the fast-charging EV charger proves to be an economically feasible system compared to a grid-based system.                                                                         | economic benefit for F-SCS is 166.1 € and REF-SCS is -6.65€.                                |
| [45] | 2023 | Onboard                                  | ×                 | ×                 | Robust and single-input adaptive fuzzy logic-tuned Perturb and Observe process and multi-layer, multi-order generalized discrete integrator-based adaptive Control of EV charging takes place through an AC bus supplied by solar PV. | Tracking time is 5 ms. Dynamic efficiency is more than 99%. The dynamic response is faster. |
| [46] | 2023 | On board                                 | ×                 | ×                 | This work presents an effective structure for light Plug-in EVs at an economical cost.                                                                                                                                                | The cost of the proposed converter is \$ 178.6.                                             |
| [47] | 2024 | Offboard/onboard                         | ×                 | ×                 | AC and DC ports in an EV can be charged using the AC grid and solar PV, respectively, to reduce charging time.                                                                                                                        | EV charging time is reduced by 50%.                                                         |
| [48] | 2024 | Onboard                                  | ×                 | HV and LV battery | This EVCS offers multiple modes, such as V2G, G2V, and HV-to-LV battery, achieving high power density and efficiency.                                                                                                                 | Maximum efficiency is 98.2% across all modes.                                               |
| [49] | 2024 | Offboard                                 | ×                 | ×                 | The dual-control method is used across different operating modes to improve power quality.                                                                                                                                            | THD is 2.008%                                                                               |

**Table 2.** EV charging methods (continue)

| Ref. | Year | Conductive charging (onboard / offboard) | Wireless charging                  | Battery swapping | Remarks and suggestions                                                                                        | Metrics                                                        |
|------|------|------------------------------------------|------------------------------------|------------------|----------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------|
| [50] | 2026 | ✗                                        | Series-series compensated wireless | ✗                | It improves energy extraction from solar PV across different modes, such as solar-only, grid-only, and hybrid. | Maintains the 240 V, 32 A output for different modes.          |
| [51] | 2025 | ✗                                        | Dynamic wireless charging (DWC)    | ✗                | A solar PV-integrated DWC system effectively mitigates the highest power demand on the grid.                   | Peak power demand on the electrical grid is lowered by 18.7 %. |

✓ - used    ✗ - Not used

Based on Table 2 above, wired charging is more efficient than wireless charging. But wireless chargers are important for dynamic wireless charging systems when the vehicle is in motion. By employing compensation techniques, wireless charging efficiency can be improved. In the wired charging method, the following points are concluded from Table 2:

- a) When DG or grid-connected EVs are used, then onboard charging is preferable. For a solar PV/energy storage facility in a power system, an off-board charger is preferable with optimized converter technologies.
- b) When the EV system rating is high, off-board charging is preferable and also leads to higher installation costs.
- c) The onboard charger provides slower charging than off-board charging.
- d) Onboard chargers are suitable for light plug-in vehicles.
- e) For V2G, G2V technology can be implemented more easily in onboard charging because of recent advancements in converter topologies and intelligent control of power systems.

BSS is an emerging technology, with research focusing on financial models, battery scheduling to meet EV demand, and the standardization of battery size and type. Conductive charging also offers potential to improve supply quality and viability for both users and providers.

Current work is fragmented, focusing on isolated components (e.g., converters, control methods, or efficiency improvements) rather than the end-to-end ecosystem. Integrated planning that combines energy sources, intelligent control, user demand behavior, grid interaction, and long-term sustainability is underemphasized. As a result, real-world deployability, interoperability, and large-scale optimization of EV charging networks remain insufficiently addressed in the above research works.

## 4. EV Technology

EV technology is rapidly evolving, and these vehicles are becoming more mainstream as governments, automakers, and consumers push for cleaner, greener transportation options. These vehicle technologies are divided into 4 major techniques [52].

### 4.1 Battery Electric Vehicles (BEVs)

As the acceptance of battery EVs rises to the forefront of mainstream transportation systems, their implications for achieving Sustainable Development Goal 13 for climate action become increasingly meaningful [53]. BEVs run solely on electricity stored in onboard batteries, producing near-zero emissions. Powered by large lithium-ion packs, they charge via home or public stations. Examples include the Rivian

R1T, Chevrolet Bolt EV, Nissan Leaf, and Tesla Model 3. Advantages include zero tailpipe emissions, Lower operating costs, Quiet operation, and government incentives for purchasing BEVs [54].

#### 4.2 Hybrid Electric Vehicles(HEVs)

HEVs join an internal combustion engine (ICE) with an electric motor and a small battery. HEVs rely on regenerative braking and ICEs to charge the battery, and are not plug-in. The battery is typically smaller than in BEVs because it is recharged via regenerative braking and engine power. Examples of HEVs include the Toyota Prius, Ford Escape-Hybrid, Honda Insight, and Lexus RX Hybrid. Advantages include better fuel efficiency than conventional gasoline cars, no need for charging infrastructure, and generally lower emissions [55].

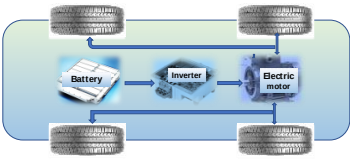
#### 4.3 Plug-in Hybrid Electric Vehicles(PHEVs)

PHEVs are hybrids with larger batteries that can be boosted at a charging station or at home. They can drive short distances on electric power alone and switch to the internal combustion engine when the battery is low. With proper energy management techniques, a PHEV can be designed to improve performance [56-57]. Examples include the Toyota Prius Prime, Mitsubishi Outlander PHEV, and Chevrolet Volt. Advantages include a longer electric-only range than standard HEVs, the ability to drive in electric-only mode for short trips, reduced fuel consumption, and greater flexibility.

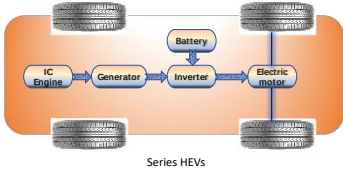
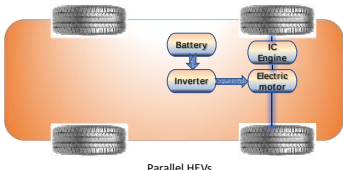
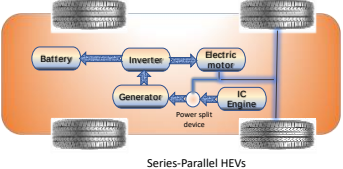
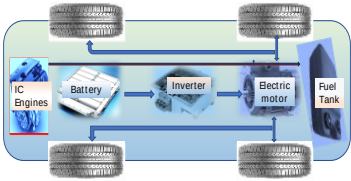
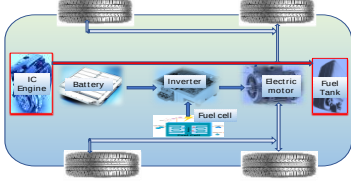
#### 4.4 Fuel Cell Electric Vehicles (FCEVs)

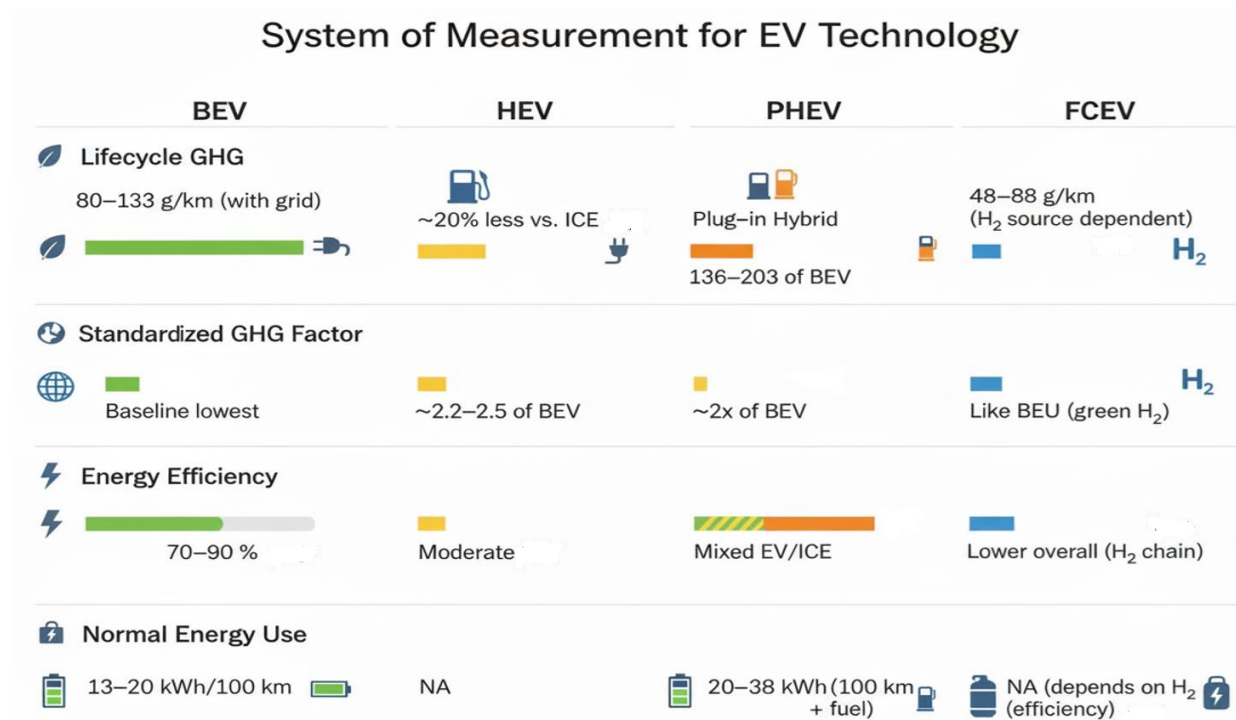
FCEVs are another type of EV that do not rely on a battery to store electrical energy. FCEVs produce electricity via a chemical reaction in a hydrogen fuel cell, producing water and heat as byproducts. Hydrogen is stored in high-pressure tanks and reacts with oxygen to power the vehicle [58]. FCEVs use electricity from the fuel cell to power the motors and emit only water vapor. They offer zero emissions, fast refueling, and long range, but cost more than BEVs or ICE vehicles because of limited hydrogen refueling stations and complex production processes [59]. Fuel cells are more efficient than ICEs but generally less efficient than BEVs. Examples of FCEVs include the Hyundai Nexo, the Toyota Mirai, and the Honda Clarity Fuel Cell. Table 3 compares components, features, and challenges of various EV technologies.

**Table 3.** Different EV Technologies with their components, features, problems, and challenges

| EV Technology | Components                                                                          | Features                                                                                                                | Problems                                                            | Challenges                                                                                |
|---------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------|-------------------------------------------------------------------------------------------|
| BEVs          |  | Zero emissions.<br>Independent of oil.<br>Economical.<br>Low repairs.<br>Diminished noise pollution.<br>Simple driving. | Limited driving range and speed, long recharge time, and high cost. | Limited range, longer charging times, and uneven availability of charging infrastructure. |

**Table 3.** Different EV Technologies with their components, features, problems, and challenges (continue)

| EV Technology | Components                                                                                                                                                                                                                                                                                                                             | Features                                                                                                                   | Problems                                                                                                                  | Challenges                                                                                                                          |
|---------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| HEVs          |  <p>Series HEVs</p> <hr/>  <p>Parallel HEVs</p> <hr/>  <p>Series-Parallel HEVs</p> | <p>Environmentally friendly, regenerative braking, electric motor support, smaller engines, and higher resale value.</p>   | <p>Less power. Expensive. Poor handling. Battery replacement is costly.</p>                                               | <p>Still relies on gasoline, has complex powertrains that increase maintenance costs, and offers a limited electric-only range.</p> |
| PHEVs         |                                                                                                                                                                                                                                                     | <p>Zero emissions, efficient in traffic, smooth operation, fewer fuel cells, and tax benefits.</p>                         | <p>Relatively expensive, complex maintenance, battery life concerns, and uncertain resale value.</p>                      | <p>Higher upfront cost, still uses gasoline (not fully emissions-free), and depends on charging access for electric range.</p>      |
| FCEVs         |                                                                                                                                                                                                                                                     | <p>Renewable, widely available, supports zero-carbon, zero-emission, efficient operation, and enables rapid refueling.</p> | <p>High costs due to hydrogen production, fuel cell investment, and the challenges of hydrogen storage and transport.</p> | <p>Limited hydrogen refueling stations, costly sustainable hydrogen production, and expensive fuel cell technology.</p>             |



**Figure 4.** Comparison of different types of EV technology -system of measurement [60-63]

Figure 4. provides a comparative analysis of various EV technologies across key performance parameters. The choice of technology depends on use, infrastructure, cost, and environmental goals. BHEVs suit urban drivers who need daily electric use and combustion backup for long trips. BEVs are ideal for efficient driving in areas with limited charging infrastructure. FCEVs are well-suited to long-distance or heavy-duty applications, offering quick refueling at locations with hydrogen infrastructure. Current studies largely focus on individual technologies in isolation, with limited emphasis on integrated energy systems, interoperability, and cross-platform optimization. Furthermore, issues such as lifecycle sustainability, large-scale deployment feasibility, and dependence on charging or hydrogen infrastructure remain to be addressed.

## 5. Converters used in EVs

In EVCs, converters are critical components that enable smooth, efficient power transfer from the grid or non-conventional energy sources to the EV battery. These converters transform and regulate electrical power from the power source into the appropriate form for EV charging. Various types of converters are commonly used in EVCs [64].

### 5.1 AC - DC Converters (Rectifiers)

DC power supplies EV batteries, while charging stations typically supply AC from the grid. For Level-1 and Level-2 charging, an on-board charger is preferable, where converters in the vehicle supply the battery with DC power. In DC fast chargers (Level 3), the AC taken from the grid is first changed to DC outside the vehicle, meaning off-board chargers.

### 5.2 DC - DC Converters

A DC-to-DC converter regulates DC power flow within the charging system. In some DC fast chargers, a DC-to-DC converter is used to regulate the charging current to the vehicle's battery, ensuring the correct voltage and current are applied for efficient and safe charging [65].

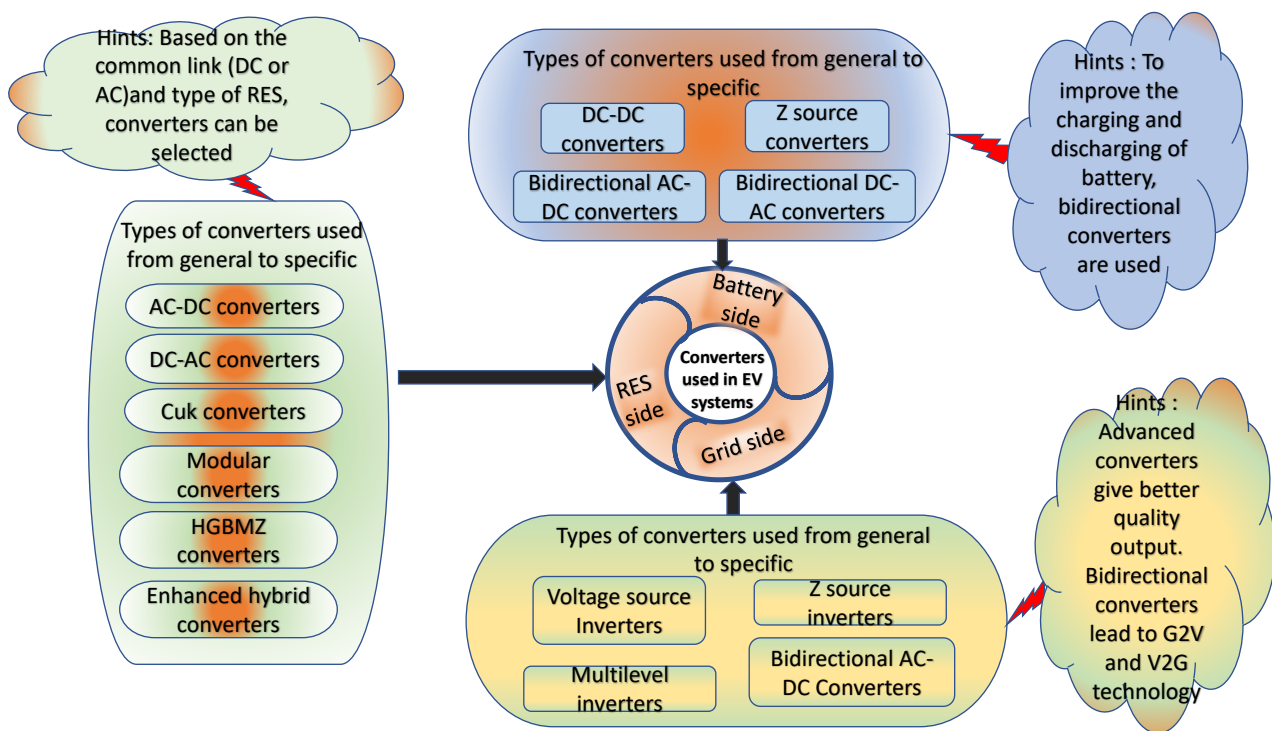
### 5.3 Bidirectional Converters ( V2G/G2V)

Bidirectional converters enable a two-way flow of electricity. While standard chargers only provide electricity to charge the vehicle, bidirectional charging allows the vehicle to send energy back to the grid, creating a V2G system. In bidirectional charging systems, the EV not only receives power but also returns

saved energy to the grid. This helps stabilize the grid and reduce THD, particularly during high-demand periods or when renewable energy sources are intermittent [66].

#### 5.4 AC to AC Converters

AC-to-AC converters are used in charging stations that need to interface with certain industrial or specialized EVs at specific voltages and frequencies. Some AC-AC converters are used in wireless (inductive) charging systems, where AC is converted to a different frequency for wireless power transmission [67]. When wind energy is used to charge EVs, these converters must transfer power at a specified level. Converters play a dynamic role in EVCSs by transforming and regulating electrical energy, ensuring safe and efficient charging, from basic AC-to-DC converters for Level-1 or Level-2 charging to advanced DC-DC converters for fast and bidirectional charging systems. These components are needed to ensure smooth, reliable charging. As the EV market grows, advancements in converter technology will continue to support faster, more efficient, and more versatile charging options [68]. The choice of power electronics converters in popular EVs depends on factors that affect the vehicle's efficiency, performance, compatibility with the power grid, design, charging infrastructure, and energy management requirements. Table 4 lists the converters used on the grid, RES, and battery storage sides, along with their purposes.



**Figure 5.** Converters used in EV systems [from Table 4]

Figure 5 summarizes the types of converters used on the grid, RES, and battery sides, and also suggests selecting a better converter from Table 4 below. Current research has limited capability for seamless multi-port, bidirectional power flow among renewables, storage, EVs, and the grid under dynamic conditions. In addition, long-term reliability, thermal management, switching losses, real-time adaptive control, and interoperability standards need improvement for large-scale deployment.

Table 4. Converters used in the Grid, RES, and Batteries side

| Ref  | Year | Converters used in the grid   | Converters used in RES/hybrid sources | Converters used in a battery storage system | Purpose of the converter                                                                                                                                                                               | Metrics                                                                                                                |
|------|------|-------------------------------|---------------------------------------|---------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|
| [33] | 2023 | VSC (Bi-directional)          | DC-to-DC converter                    | DC-DC converter                             | Power exchange among the solar PV array, BES, EV, and grid is achieved.                                                                                                                                | The DC link voltage is maintained at 500 V.                                                                            |
| [37] | 2020 | Bidirectional AC-DC converter | Bidirectional AC-DC converter         | Bidirectional AC-DC converter               | Solar PV, a boost converter, and battery storage are coupled to the DC side of the AC-DC converter that supplies EV2, while the DG and grid are connected to the AC side of the VSC that supplies EV1. | In GCM mode, the current THD is 4.1%, and in DG mode, it is 1.7%.                                                      |
| [69] | 2021 | VSC                           | Boost converter                       | -                                           | VSC output is well balanced with respect to grid voltage.                                                                                                                                              | Grid voltages at balanced conditions are 213.37V, 217.31V, and 215V, and grid currents are 5.512A, 5.692A, and 5.609A. |
| [70] | 2022 | Seven-level CHBDC MLI         | Diode-based converter                 | Bidirectional DC-DC converter               | To improve voltage quality, reduce converter dimensions, and control the charging and discharging of both the storage capacity and EV batteries.                                                       | Power from PV is 4.86 kW; EV takes 1.6801 kW; storage is 1.052 kW; 1.9298 kW to the grid. THD is less than 5%.         |

| Ref  | Year | Converters used in the grid          | Converters used in RES/hybrid sources | Converters used in a battery storage system | Purpose of the converter                                                                                                                                     | Metrics                                                                                                                         |
|------|------|--------------------------------------|---------------------------------------|---------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|
| [71] | 2022 | Open DC modular multilevel converter | Open DC modular multilevel converter  | -                                           | To prefer fewer devices and greater reliability.                                                                                                             | The total number of devices has decreased to half. (=36 devices)                                                                |
| [72] | 2023 | VSC converter                        | Bidirectional converter               | -                                           | Used for EV charging or discharging.                                                                                                                         | THD is 3.3%, and settling time is 20ms, compared to the papers discussed.                                                       |
| [73] | 2024 | -                                    | DC -DC converter                      | DC -DC converter                            | A high-frequency inverter is used after the DC bus on the transmitting side of wireless power transfer, and a diode rectifier is used on the receiving side. | Power is transferred across a 100-200 mm air gap.                                                                               |
| [74] | 2021 | VSC                                  | modular converters                    | DC/DC stage converter                       | To achieve maximum power levels and obtain a fixed DC link voltage.                                                                                          | Stack efficiency is above 50 %.                                                                                                 |
| [75] | 2023 | VSI                                  | HGBMZ converter                       | -                                           | It is designed to enhance PV system efficiency by boosting voltage levels and enabling V2G.                                                                  | Converter efficiency is 93.04%                                                                                                  |
| [76] | 2025 | Bidirectional converter              | Bidirectional converter               | Bidirectional converter                     | Best converter choices and designs for EV applications.                                                                                                      | Voltage stress, current stress, voltage-gain range, conversion efficiency, power density, and switching frequency are improved. |

## 6. Optimization methods in EV

Optimization in Electrical systems is essential for improving the efficiency, sustainability, and consistency of energy generation, storage, and consumption [66]. Advanced algorithms and supervised methods optimize power flow between the grid, renewables, storage, and EVs efficiently and cost-effectively, using optimization techniques across RES, EVCS, V2G integration, smart grids, and controllers.

### 6.1 Essentials of optimization in Energy sources of EV systems:

Some key areas of optimization in Renewables-connected EV applications include maximizing energy efficiency, enhancing grid stability, minimizing costs, increasing the lifetime of energy systems, and supporting V2G operations based on the grid's actual time requirements and the battery's SoC. Battery Storage Regulator optimization in both EVs and the energy system can store excess renewable energy and release it when renewable generation is low or grid demand is elevated [77-78]. In most works, solar PV output is optimized using various methods to extract more energy. ANFIS-based control supports grid management, while fuzzy optimization minimizes EV charging costs under power and renewable constraints. In DES-based EV systems, mixed-integer quadratic optimization and Markov Decision Processes optimize energy flow among the DES, battery, load, and grid. In contrast, battery-side optimization enhances DWC revenue and reduces grid impact.

### 6.2 Essentials of Optimization in EVCS:

In the EVCS, optimization techniques control charging infrastructure and charging management, such as dynamic pricing and load balancing. Accurate forecasting of solar and wind generation, charging demand, and electricity prices enables optimal evaluation and achieves the energy remit [79-80]. The proposed design algorithm determines the required number of EVCSs, thereby increasing the system's operator reward. The PSO Optimization method used here fully estimates the modifying interdependencies and the values of financial and dependability indicators for the standalone hybrid energy power systems.

### 6.3 Multi-Objective Optimization and Advanced Optimization Techniques in EVs:

Multi-objective optimization simultaneously achieves goals such as reducing costs, maximizing renewable energy use, minimizing battery degradation, and enhancing grid stability, for optimal siting and sizing of EVCSs with PV and energy storage systems. Multi-objective optimization is used to reduce electricity costs and radiation contamination [81]. Advanced optimization techniques, including energy management strategies, smart grid integration, multi-objective optimization, and AI-based algorithms, enhance the efficiency, reliability, and sustainability of DES. Comparative studies show that optimally designed standalone hybrid charging stations offer a cost-effective, eco-friendly alternative to grid extension. Moreover, decentralized optimization and IoT-enabled real-time data collection enable dynamic energy management across smart grids and EVCSs [82].

### 6.4 Different optimization algorithms and models:

Mathematical models and optimization algorithms include linear programming, Dynamic Programming, mixed-integer linear programming, Stochastic Optimization, Genetic Algorithms (GA), and Artificial Intelligence. Optimization in distributed energy systems for EVs improves energy efficiency, reduces costs, and enhances overall performance and sustainability [83]. The CAPSA algorithm optimizes EV current and power quality, while ANC-based control enhances power exchange, DG loading, and power factor. A fuzzy-tuned P&O and MMGDI AC controller regulates the boost converter and grid-tied inverter, whereas the Whale Optimization Algorithm improves renewable integration. Additionally, a two-stage robust optimization model minimizes 24-hour operational costs associated with energy losses, power transactions, DG control, and battery/EV operations. All system factors can be optimized to improve overall performance. Table 5 summarizes the objectives of different optimization techniques and control algorithms, as well as their applicability.

**Table 5.** Different optimization techniques and control algorithms with the objective.

| Ref. | Optimization / special control algorithm                                       | Applied in/among                   | Objective of optimization or control algorithm.                                                                                                             | Year | Metrics                                                   |
|------|--------------------------------------------------------------------------------|------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|------|-----------------------------------------------------------|
| [8]  | A planning algorithm is employed                                               | EVCSs                              | To obtain the needed number of EVCSs, which increase the system's operator reward.                                                                          | 2023 | 1355 EVs for 100% of SOC                                  |
| [34] | MPPT algorithm                                                                 | Solar PV                           | Harvesting more energy from solar PV.                                                                                                                       | 2018 | Power to EV is 421W, and to BES is 35W.                   |
| [84] | The merged integer Quadratic.                                                  | DES, load, and grid                | Confirms managing energy, which minimizes the cost function.                                                                                                | 2024 | --                                                        |
| [85] | SSOA assisted the fuzzy controller.                                            | Solar PV                           | Harvesting more energy from solar PV.                                                                                                                       | 2024 | MPPT efficiency of 97.12%                                 |
| [86] | Whale optimization algorithm(WOA)                                              | RES                                | Raising the deployment of RE and lowering reliance on non-renewable energy sources                                                                          | 2023 | COE is nearly 0.25\$/KWhr.                                |
| [87] | Optimization policy                                                            | EV-charging                        | Helps in dynamic wireless charging, earnings, and reduces the grid effect by altering charging and electricity purchasing at each prospect.                 | 2023 | Charging costs cut by 50%.                                |
| [88] | Fuzzy-based optimization algorithm.                                            | Pricing based on RES availability  | Increases the charging fee based on power convenience, EV power load, charging period, and prevailing tariff, with renewable use serving as an upper limit. | 2023 | Reduces energy cost by 74.67%.                            |
| [89] | Optimization and comparative consideration.                                    | Standalone hybrid charging station | Showing that choosing an optimum is a reasonable, environmentally friendly alternative to grid extension.                                                   | 2023 | The system's capacity shortage is 0.09%.                  |
| [90] | Two stage robust day-ahead optimization model                                  | Pricing based on DG and battery    | To reduce many costs connected with energy losses, power gains, and load restrictions.                                                                      | 2024 | Efficiency is improved by at least 5% over other methods. |
| [91] | Multi-objective optimization, Fuzzy inference system-based planning framework. | EVCSs                              | Optimal siting and sizing of EVCSs are used to reduce electricity costs and radiation contamination.                                                        | 2025 | Net energy cost reduced by 42%.                           |
| [92] | BBO algorithm                                                                  | EMS                                | Optimizes the production and consumption of comparable hydrogen in the microgrid.                                                                           | 2021 | -                                                         |
| [93] | Energy management algorithm                                                    | PV, EV, BESS, and grid             | Balance the power flow among all DES and EVs.                                                                                                               | 2024 | Maximum 1 % and 1.25% voltage deviation.                  |
| [94] | Grid topology optimization framework                                           | Solar PV                           | Optimal placement of feeders, substations, and interconnections to minimize overall price and technical losses.                                             | 2026 | Voltage and current THD are less than 2%.                 |

| Ref. | Category | Efficiency | Cost Reduction | System Capacity | Power Quality |
|------|----------|------------|----------------|-----------------|---------------|
| [8]  | EVCS     | —          | —              | High            | —             |
| [34] | RES      | Medium     | —              | Low             | —             |
| [84] | RES      | —          | —              | —               | —             |
| [85] | RES      | High       | —              | —               | —             |
| [86] | RES      | Medium     | Medium         | —               | —             |
| [87] | EVCS     | —          | High           | —               | —             |
| [88] | Pricing  | —          | Very High      | —               | —             |
| [89] | EVCS     | —          | —              | High            | High          |
| [90] | Pricing  | Medium     | —              | —               | —             |
| [91] | EVCS     | —          | High           | —               | —             |
| [94] | RES      | High       | —              | —               | High          |

**Figure 6.** Comparison of efficiency, cost reduction, system capacity, and power quality [from Table 5]

Cost optimization in EV charging systems (EVCS) focuses on reducing energy costs while also enhancing scalability and capacity. In Figure 6, renewable energy systems (RES) focus primarily on efficiency and power quality. Most studies emphasize these aspects, but pay limited attention to maintaining stable system parameters. In practice, faults and disturbances can cause voltage instability, highlighting the need for robust control strategies to ensure reliable operation.

## 7. Future Recommendations

Based on a survey of EV charging research, the following are recommended as future research thrust areas.

### 7.1 Energy sources for EV

Solar energy is ideal for home and public EV charging, while wind supports grid-level supply in windy areas. Hydropower provides a reliable base load, and biomass/biogas serve remote or hybrid stations. Green hydrogen powers fuel-cell EVs in heavy transport. Used EV batteries store excess renewable energy, and AI and IoT optimize charging and system monitoring. Smart infrastructure, policies, and storage accelerate EV adoption as key components of a decentralized, renewable energy ecosystem.

### 7.2 EV charging methods

Optimal EV charging integrates Level-2 AC for daily use, DC fast charging for long trips, and battery swapping for commercial fleets. Wireless charging supports autonomous vehicles. Future EV charging should prioritize faster, smarter, safer, and greener systems that leverage AI, wireless technologies, V2G, and renewables to enable sustainable growth.

### 7.3 EV Technology

Future research should focus on BEVs for their scalability, zero-emission operation, and compatibility with renewable energy, making them ideal for personal and urban use. FCEVs are well-suited to heavy-duty and long-range applications and support the development of green hydrogen. PHEVs offer a temporary solution in areas with limited EV infrastructure, while HEVs are becoming less relevant.

#### 7.4 Converters used in EVs

Future research on EV converters should focus on efficiency, power density, thermal management, and bidirectional energy flow. Multilevel converters (e.g., neutral-point-clamped and flying-capacitor) reduce switching losses and improve output quality in high-voltage applications. Soft-switching techniques, such as resonant converters and zero-voltage switching, minimize EMI and improve system efficiency. Bidirectional converters support V2G and regenerative braking. Advancing wide-bandgap semiconductors (SiC, GaN) enhances switching speed, thermal performance, and compactness. Modular and integrated designs reduce size, weight, and cost while improving reliability, enabling smarter, high-performance, and sustainable EV power management.

#### 7.5 Optimization methods in EV

Future research in EV optimization should focus on battery management, powertrain efficiency, energy use, and route planning. Advanced algorithms such as genetic algorithms, particle swarm optimization, and model predictive control can maximize battery life and minimize degradation. Optimizing power distribution among motors, converters, and regenerative braking improves overall efficiency. In charging infrastructure, load forecasting and dynamic pricing reduce grid strain and costs. AI-based route and driving optimization lowers energy use and enhances vehicle range. Multi-objective optimization can ensure safe, energy-efficient thermal management of batteries and electronics. Integrated frameworks that combine vehicle dynamics, energy flow, thermal control, and charging policies, along with real-time, adaptive, AI-driven solutions, will be key to connected and autonomous EVs.

### 8. Conclusions

This review paper on electric vehicle systems highlights the rapid growth and multidisciplinary nature of this developing field. Non-conventional energy resources such as solar PV and wind are increasingly integrated into EV charging infrastructure, promoting sustainability and reducing reliance on fossil fuels. Conductive charging, particularly on-board charging, offers higher efficiency than other methods and supports the implementation of V2G and G2V technologies through converter topologies and intelligent controllers in power systems. Dynamic wireless charging systems are the most sought-after technology for vehicles in motion and are the leading technique in some countries for consumers' convenience zones. BSS is a flourishing technique, driving the application of economic principles, the planning of battery-based EVs, and the standardization of battery sizes. Among various charging methods, Level 2 AC charging for regular use and DC fast charging for long-distance travel are emerging as the most practical solutions. In terms of EV technologies, BEVs currently offer the best balance among performance, scalability, and environmental impact, although FCEVs show potential to meet EV demand and support long-term applications. Power converter topologies are undergoing substantial modernization, with trends favoring multilevel, soft-switching, and bidirectional designs, enhanced by wide-bandgap semiconductors that enable superior efficiency and compactness. Optimization techniques for energy management, cost minimization, grid stabilization, and power quality improvements enhance EV system-level performance, and artificial intelligence is playing an increasingly prominent role in real-time decision-making and predictive control. Ongoing research and development across these domains will be essential to overcome current constraints and accelerate the transition to cleaner, smarter transportation.

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